QH545
.F5
S37
1996

United States
Department of
Agriculture

Forest Service

Pacific
Northwest
Region

**Wallowa-Whitman
National Forest**

**Blue Mountains
Pest Management Zone**

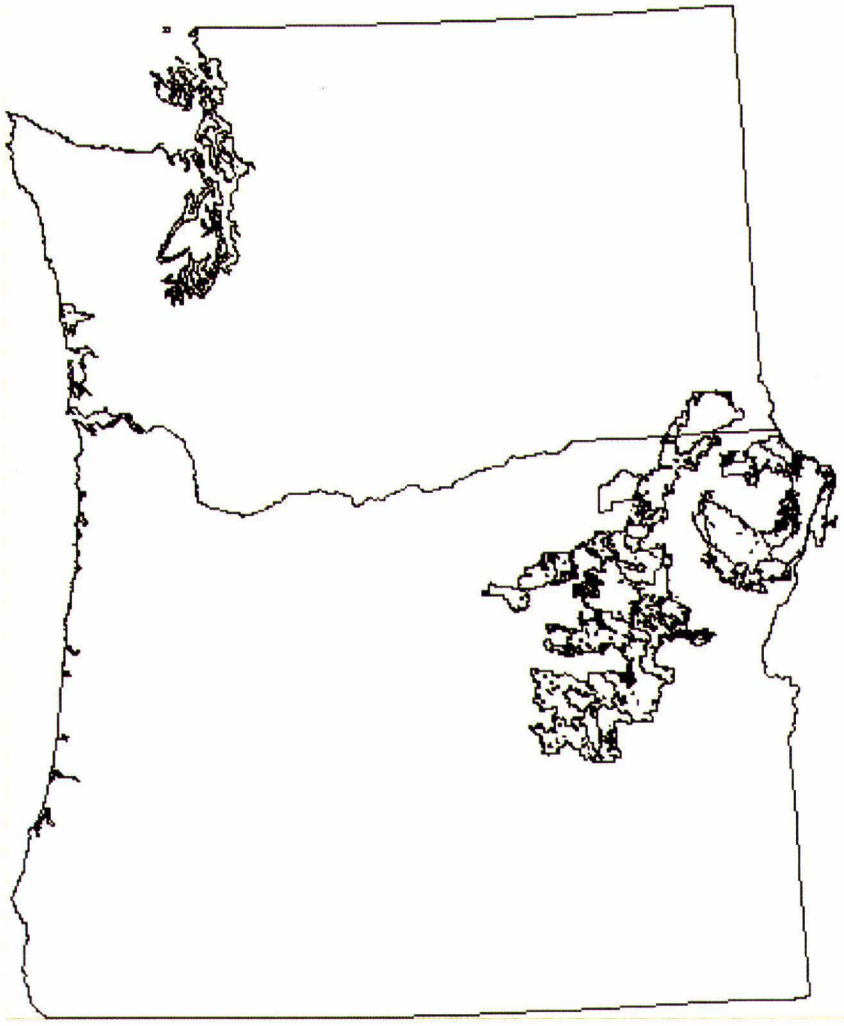
BMZ-97-1
December 12, 1996

Entomological Concerns Regarding Burn Characteristics and Fire Effects on Tree Species During Prescribed Landscape Burns:

Burn severity guidelines and mitigation measures to minimize fire injuries

Donald W. Scott
John Szymoniak
Victoria Rockwell

Douglas-fir beetle infestation on lower bole of fire-scorched Douglas-fir.



Caring for the Land and Serving People

ROCKY MOUNTAIN RESEARCH STATION LIBRARY
FORT COLLINS CENTER
240 W PROSPECT RD
FORT COLLINS, CO 80526-2098

Entomological Concerns Regarding Burn Characteristics and Fire Effects on Tree Species During Prescribed Landscape Burns:

Burn severity guidelines and mitigation measures to minimize fire injuries

Donald W. Scott
Blue Mountains Pest Management Zone
Natural Resources
Wallowa-Whitman National Forest
La Grande, Oregon 97850

John Szymoniak
Ecosystem Protection
Wallowa-Whitman National Forest
Baker City, Oregon 97814

Victoria Rockwell
Natural Resources
Wallowa-Whitman National Forest
Baker City, Oregon 97814

December 12, 1996

Report No. BMZ-97-1

QH545
.F5
.S37
1996

Table of Contents

Introduction 1

Insect Response to Altered Landscapes 3

Fire Effects On Conifers 11
- Effects of Seasonality on Survival of Fire-injured Conifers 12
- Root Damage 14
- Crown Damage 17
- Cambium Damage 19

Guidelines and Indicators to Assess Fire Severity and Potential for Insect-caused Mortality 22
- Discussion of Burn Severity Guidelines 31
  - Special Cases 31

Measures to Minimize Fire Injuries From Prescribed Burns 34
1. Determine acceptable mortality "risk" levels for desirable trees. 34
2. Minimize crown injury. 34
3. Minimize root injury. 34
4. Minimize stem injury. 35
5. Modify characteristics of available fuels to optimize conditions for desired fire behavior. 37
6. Modify ignition patterns to manage the amount of fuel that is burning at any one time. 38
7. Reduce heavy fuels during harvest operations or use a 2-tiered fuels treatment approach when predicted fuel loadings are excessive and could result in flame lengths that would cause excessive injury to crowns. 39
8. Utilize the mosaic burn patterns of landscape underburning to emulate the diversity of natural, historic fire patterns and processes across the landscape. 39

Summary 40

Acknowledgement 41

Literature Cited 42

Entomological Concerns Regarding Burn Characteristics and Fire Effects on Tree Species During Prescribed Landscape Burns:

Burn severity guidelines and mitigation measures to minimize fire injuries

Introduction

Disturbances, especially fire, are important agents of change in the wildland ecosystems of the Interior Columbia River Basin (Morgan et al. 1996). Much has been written this decade concerning forest health and the strong linkage to fire in the ecosystem, or the lack thereof. Fire's role in the shaping of ecosystems is better understood now than at any time since the European settlement of North America. We have become familiar with the terms fire regime, fire intensity, and disturbance resiliency; and their usage in discussions on ecosystem management have become commonplace.

Much of what we have learned in the Blue Mountains of Northeast Oregon has led to the broad conclusion that these forests are disturbance prone and that some of our past actions may be magnifying the effects of these disturbance agents. Assessment after assessment have reached the same conclusion: portions of the Blue Mountains Forest ecosystem are at risk of undergoing major disturbance events from fire, insects, or diseases within the near term. Much of the forests that are at risk cannot be sustained in their present condition. There is ample evidence to indicate that in spite of the risk, efforts must move forward at landscape scales to ensure that these disturbance events can function, within the range of social expectations. At the same time we must also provide for the ecological need of landscapes that dèpend upon a variety of disturbance processes. The relationships between these complex disturbance factors are an intricate weave of climatic, evolutionary, anthropogenic, biological, and stochastic processes.

These forests are by no means unique in this risk category across the West; it is because we know them the best that we are concerned with how we leave them for future generations. Two of the most pronounced disturbance processes during the last several decades have been wildland fire and insect epidemics. Previous efforts to exclude these two disturbance elements by means of fire suppression and aerial spray programs, respectively, were viewed as necessary actions to "protect" the ecosystem when they were first implemented. That view is changing. We are now learning that some of these actions may only be delaying the effects of these processes on the landscape. Optimistically, the delay has bought us valuable time to increase our understanding of these landscapes and the processes that influence them. However, an undesirable effect of this delay is the current potential for these disturbance processes to act at a scale that may be beyond human and biological tolerances.

Prescribed landscape burns are being planned and implemented to respond to this increased awareness of fire's role in both the shaping of ecosystems and the reduction of risk from unwanted wildland fire. Indications are that this trend will continue, and in fact increase into

the future. Though presumed to be beneficial overall to the landscape, these prescribed burns cause various first-order fire effects on trees that may at times promote unintended consequences to forest resources. Fire-caused mortality may occur for several years after a fire. Generally this delayed mortality is expected and is within acceptable levels to the resource manager. Often it is necessary for meeting planned wildlife snag recruitment objectives. Insect infestations after a prescribed fire can also provide habitat diversity for the animal species they attract to the insect-killed trees, and initiate substantial changes in stand structures. However, for these effects to be judged successful, they must occur at appropriate scales. A landscape burn ideally emulates a low-intensity surface fire that creates a limited number of snags across the landscape. A landscape burn out of prescription is a high-intensity burn that creates an excessive number of snags over a large area. This latter situation probably does not serve resource needs very well and rarely meets management objectives. Nor does a landscape prescribed burn that initiates a large-scale, fire-induced insect epidemic.

Bark beetles are the number one biological agent of tree mortality because of tree wounding by fire in the northeast of Oregon and southeast of Washington. Tree-killing bark beetles of the genus *Dendroctonus* are pervasive in the forests of the Blue and Wallowa Mountains. Large fire events and the frequent presence of insects in high numbers after large fires are, in part, a manifestation of how humans have unintentionally manipulated the landscape to encourage both stand-replacement fires and bark beetle outbreaks. Bark beetles readily respond to host trees when trees are injured by fire; but as we have observed, usually only when trees sustain certain levels of injury.

While their presence may go unnoticed altogether, or may be manifested by the fading of relatively few symptomatic trees within a healthy stand, bark beetles have the remarkable ability--via their pheromone system--of rapidly rallying large numbers of individuals together to exploit an abundance of favored habitat, such as fire-injured trees. Beetles may be drawn in from adjacent stands, and possibly over several miles (Miller and Patterson 1927), once an attractive pheromone source is established by pioneering beetle attacks on the host. Colonization of hosts by bark beetles is usually rapid and efficient given their strong flight ability and small size. These characteristics aid their dispersal and host selection processes by both directed flight and more serendipitous movement by wind currents.

In addition to achieving specific resource management goals with landscape underburning, it is important that prescriptions also minimize the post-fire mortality of desirable trees. Wildland prescribed fires, particularly landscape burns due to their size and potentially long duration, can result in variable levels of damage to conifers. Insects attracted to fire-injured trees or stands may contribute substantially to post-burn tree mortality. Models have been developed to predict tree mortality from fire (see Peterson 1983, 1984; Reinhardt and Ryan 1988; and Ryan et al. 1988), and for forecasting outbreaks of certain insects (see Berryman 1986), but it is much more difficult to predict tree mortality from a combination of fire and subsequent beetle attack. Given this fact, it is of paramount importance to integrate the factors affecting insect populations that are related

to fire-injured trees with fire behavior, as suggested by Ryan (1988), to develop appropriate prescriptions that meet both resource and fire management objectives. This document has been prepared to address fire-insect relations, with applicability to prescribed fire situations. Specifically, the purpose of this document is: (1) to describe some of the fire effects on conifers that are of entomological concern; (2) to provide tentative burn-severity guidelines for determining acceptable levels of tree mortality risk and to help identify those areas of a landscape burn that warrant closer monitoring to detect post-fire infestations of insects that may develop to outbreaks; and (3) describe several mitigation actions that will help reduce the level or severity of injuries to desirable trees during prescribed landscape underburns so as to reduce the attraction of tree-killing bark beetles to these trees.

Insect Response to Altered Landscapes

Before we can discuss the effects of fire on conifers and the relationship of tree wounding by fire to insect colonization, it is necessary to put both fire and insects in proper perspective as disturbance agents on the landscape. Scott (1996) documented the fluctuations of insect populations in presettlement and modern times relative to changes in landscape vegetation patterns as influenced by natural fire regimes. To facilitate a discussion on insects and fire as disturbance agents in the forest ecosystem, this document, with minor modification, has been reproduced in its entirety in the remaining paragraphs of this section.

Fire and insects, as well as forest pathogens, are major disturbance agents on the forest landscape. Understanding the nature and function of insects in ecosystem process necessitates an ecological discussion of the interactions of vegetation, fire, and insects and the role of these interactions in altering landscapes. The range of these interactions pose challenges to the resource manager, who is responsible for managing the ecosystem for resource outputs and amenities that are governed by ecological conditions and attributes of the landscape as modified by fire, insect, and disease disturbance regimes.

Considerable changes to the landscapes of the interior northwest have occurred over the approximately 150 years since arrival of, and settlement by European-Americans. These changes, reflected by altered vegetation patterns, structures and densities, frequent stand-replacing wildfires, and widespread devastating insect and disease outbreaks have emerged at the forefront of resource management concerns in recent years. It is informative to examine the influences of altered landscapes on insect populations in forest ecosystems to better comprehend the potential scope of effects on the ecosystem of management activities such as prescribed landscape burning, as a silvicultural activity to emulate the effects of natural fire regimes.

Concepts and management approaches to sustaining ecological systems began to emerge in some Regions of the Forest Service in 1991 (USDA 1992). Over the past 3 or 4 years, discussions and writings on forest health and ecosystem sustainability and management have increasingly focused on the somewhat confusing concept of **Historic Range of Variation (HRV)** or **Range of**

Natural Variability, also called **Natural Range of Variability (NRV)** to provide a basis for management actions aimed at the conservation of biodiversity within the bounds of natural ecological variability (USDA 1992). The terms are often used interchangeably. Attention usually has been focused on conditions of vegetation, diseases, insects and other animal populations, fire regimes, stream conditions, and various other natural resource entities in order to measure or estimate the state and departures of present conditions from the range of natural variability of biotic communities and species native to the area that characterized a sustainable, "healthy" ecosystem. **Natural Variability** has been described as the variability in landscape/ecosystem composition, structure, and function that has occurred through recent adaptive evolutionary time (see USDA 1992). Kaufmann et al. (1994) defined the **Range of Variability (Natural Variation)** as the spectrum of conditions possible in ecosystem composition, structure, and function considering both temporal and spatial factors. To describe this term in an historic context, they defined an additional term, **Historical Variation (Historic Range of Variation)** as the range of the spatial, structural, compositional, and temporal characteristics of ecosystem elements during a period specified to represent "natural" conditions. For the purposes of this discussion, we will use this latter term in reference to vegetation conditions and patterns. However, for disturbance processes and regimes such as insect outbreaks and wildfire events, characterization of the HRV is more appropriately defined in terms of the patch size distribution, frequency, and severity of the event or sequence of events (Swanson et al. 1994).

In the paragraphs that follow, we will develop a discussion of the influence of fire-return intervals and patterns on the HRV for insects for the presettlement time period. We use the presettlement period of time to represent "natural" conditions of disturbance regimes in the Blue and Wallowa Mountains. As Schmid and Mata (1996) point out, the HRV for insects is difficult to determine precisely. We will not attempt to undertake a description and rationale for the HRV for insects in this document. The development of that thesis is beyond the scope of this paper. In this section, we will also refer to the term "**presettlement**" as that period of time preceding settlement of the western United States by Euro-Americans (i.e., prior to approximately 150 years B.P.). The term "**pre-management**" corresponds to roughly the same period, but implies the commencement of livestock grazing in the forests and meadows, timber extraction and forest management activities, and wildfire suppression activities, without any reference to the chronological occurrence of these activities. We use these last two terms somewhat interchangeably.

The changed conditions in the forest have brought about associated dynamic natural disturbance processes that have been magnified in scale and intensity over earlier historical events. Many of the formerly pine-dominated stands of the Blue and Wallowa Mountains are now largely multi-storied in structure and mixed conifer in composition due to exclusion of fire and the selective removal of pine from stands. Fires that once burned with relatively short return-interval frequency and low intensity in the xeric pine-dominated plant communities are now catastrophic stand-replacing events over considerable area of eastside forests annually (fig. 1). Insect

outbreaks that once occurred sporadically at low or moderate levels of intensity, and less frequently at high intensity over limited areas, are now considerably more widespread and damaging. Root diseases that existed at relatively low levels across the landscape have been exacerbated by repeated partial cut harvesting to remove mostly seral species in stands. The effect of early management activities on forest lands throughout the Interior West has been to artificially accelerate these stands toward successional climax. In addition, the periodic "cleansing" by surface fires of the past--now greatly diminished in occurrence--once maintained low levels of dwarf mistletoe in coniferous stands in earlier times, now rarely play that role. The prominence of dwarf mistletoe in some stands dominated by species such as Douglas-fir oftentimes severely limits the ability to manage those stands in a healthy condition.

Fig. 1. Many decades of fire suppression have led to increased stand densities and increased forest fuel conditions. Fire disturbance regimes have shifted from frequent low-intensity surface fires to stand-replacement events.

When only the effects of vegetation changes on the insect-disturbance component are considered, an increasing trend towards development of stands less tolerant to insect depredations is revealed. Descriptions of the effects of fire on landscape patterns prior to management influences this century are first needed to gain an appreciation of how landscape patterns, and vegetation conditions within forests have changed over time and are influencing the range of variability of insects. The following briefly describes the effects of fire on a few of the vegetation series in the Blue and Wallowa Mountains where fire return intervals were frequent, and fire intensity was low.

Surface fires prior to about 1850, especially in the low and middle elevation pine-dominated landscapes, probably affected large areas due to the abundance of fine fuels on the forest floor (Agee 1994). The frequent surface fires prior to commencement of fire management activities early in this century resulted in natural landscape patterns of unbroken, open parklike stands of widely spaced tree clumps and continuous herbaceous understory (Agee 1994; Wickman 1992). Many presettlement fire-maintained ponderosa pine forests of the Blue and Wallowa Mountains probably resembled the Old Forest Single-Stratum stand structure class described by O'Hara et al. (1996). This structure contained a single stratum of medium to large, old trees of one or more cohorts. It was maintained in this condition by frequent, low-intensity--and mostly nonlethal--surface fires.

Fire regimes appeared to have been even more frequent in the dry Douglas-fir, white fir, and grand fir series of eastside forests because these plant associations likely produced more fine dead fuels needed to carry the next fire than did the ponderosa pine series (Agee 1994). Like the ponderosa pine series, the influence of frequent low-intensity fires in these drier Douglas-fir and true fir plant communities was to keep forests open and parklike, with fire-resistant ponderosa pine present as a seral dominant (Agee 1994). The common occurrence of stand-replacement fires differentiated the fire effects in the cooler, moist grand fir series from those of warmer and drier plant associations within the series. Natural fire regimes in the cooler grand fir series were characterized by longer fire-return intervals, and fires occurred there with more moderate severity (Agee 1994). Overall, the effect of pre-management natural fire regimes in the Douglas-fir, white fir, and grand fir series was the development over time of a more variable spatial and temporal landscape pattern than in ponderosa pine forests (Agee 1994).

A shift from these early (pre-management) landscape patterns rapidly evolved in the eastside forests with the advent of fire exclusion policy, timber harvesting practices, and livestock grazing. A thorough review of the history of forest management describing the effects of these activities, and others of less importance to the development of landscape patterns and vegetation in eastern Oregon and Washington is given by Oliver et al. (1994). Johnson et al. (1993) describe the role of disturbance processes in enhancing biological diversity.

Fire suppression, more than any other management activity or process has resulted in the most dramatic vegetation changes in eastside forests over those of the natural fire regime. Accordingly, fire has been termed the most historically influential disturbance on eastside landscapes (Hessburg et al. 1994). Over time, fire exclusion and suppression have altered landscapes from stands composed of predominantly seral, fire-adapted species, to stands comprised mostly of shade-tolerant, fire-susceptible species; stand structure has gone from predominantly open, parklike to the development of dense understories; and fuels have accumulated to levels that exceed historic conditions (Johnson et al. 1993; Parsons and DeBenedetti 1979). These vegetation changes reflect landscape conditions clearly outside the historic range of variation under natural fire regimes.

Similarly, insects have responded in kind. Outbreaks of defoliators have become more widespread and damaging in the latter half of this century (Gast et al. 1991). Indeed, during 1986, the peak year of the most recent western spruce budworm (*Choristoneura occidentalis* Freeman) outbreak (1980-1992), over 3.75 million acres of forest land on the Malheur, Umatilla, and Wallowa-Whitman National Forests were defoliated (Gast et al. 1991). Moreover, research shows that budworm outbreaks in the northern Blue Mountains have occurred with greater frequency during the 20th Century than during earlier times dating back to 1700 A.D. (Swetnam et al. 1995). It is widely believed that the resultant stand damage and size of these defoliator outbreaks are closely linked to the changes in vegetation and landscape patterns that have occurred mostly since fire suppression began early this century. Outbreaks earlier in this century were small and widely scattered, subsided quickly, and resulted in little or no damage (Dolph

1980; Stipe 1987). Some of these outbreaks were treated with DDT which may have terminated them prematurely, and disrupted natural feedback processes that would have otherwise led to population collapse.

Likewise, numerous examples of increased bark beetle activity linked to vegetation changes could be cited for nearly any conifer series occurring in the interior West. Changed stand conditions have led to increased stand susceptibility to beetles. In addition, widespread weakening of host trees by budworm and Douglas-fir tussock moth (*Orgyia pseudotsugata* (McDunnough)) defoliation, coupled with moisture stress and overstocked conditions, have created enormous habitat across the landscape for bark beetles to colonize and kill. Epidemics of Douglas-fir beetles (*Dendroctonus pseudotsugae* Hopkins) and fir engravers (*Scolytus ventralis* LeConte) developed in weakened stands near the end of the defoliator outbreaks; and populations that built up are still active in some stands today, although at considerably reduced levels due to depletion of suitable host trees. Overstocked second-growth ponderosa pine stands that have undergone recent mountain pine beetle (*Dendroctonus ponderosae* Hopkins), western pine beetle (*Dendroctonus brevicomis* LeConte), and pine engraver beetle (*Ips pini* (Say)) epidemics are classic cases of plant associations developing into high beetle-risk conditions, without the benefit of natural thinning that resulted from the frequent, low-intensity surface fires of the natural fire regimes of the past. Bark beetles acting on these stands may further destabilize the system by causing significant changes in species composition and disrupting forest production (Mason, 1993).

Presettlement fires provided an important process in forest ecosystems by maintaining lower densities of mostly seral pine and larch in the warmer and drier low- and mid-elevation plant associations while replacing stands on a less frequent basis in the cooler, moister, high-elevation spruce-fir stands, and in the moist or wet grand fir plant associations. Lower densities helped to keep insect populations at mostly endemic levels. Insect epidemics occurred less frequently. Insect epidemics are not recent phenomena of forest ecosystems; they have occurred for millennia as disturbance and stabilizing processes. But, as Schmid and Mata (1996) point out, recent or current insect outbreaks may or may not be outside their range of natural variation, depending on whether we are referring to magnitude or frequency, or both. Little evidence or data exist to precisely describe insect populations--especially during presettlement times--in anything other than relative terms, such as "endemic" or "epidemic," or "low," "moderate," or "high." However, if we consider the interactions of insects, their environment, vegetation patterns, and fire regimes, we begin to gain a clearer understanding of the processes that help define and govern the variability of insects within forest ecosystems.

Consider first, for example, development of vegetation under different fire regimes. Under more frequent fire-return intervals, presettlement vegetation patterns were a mosaic of patches of different age classes with the patches consisting of mostly early- to mid-seral successional species and even-aged within. Gaps were created in the forest when mortality occurred in small, even-aged groups of trees. These gaps were soon reseeded during the next good seed year and

moisture conditions for reestablishment of yet another even-aged group (Agee 1993). On warm, dry sites these stands were characteristically dominated by ponderosa pine. Western larch, Douglas-fir, lodgepole pine, or ponderosa pine tended to dominate on the grand fir sites, partly owing to a fire regime of variable severity in this vegetation series (Agee 1993). According to Agee (1993), as these young groups grew to sapling size and began to shed needles, subsequent fires would kill new seedlings that grew back in the openings during the next fire event. Hence, frequent fire intervals maintained the even-aged, clumped tree pattern over time. From all accounts, these stands tended to have low to moderate stocking which caused them to be described as open and parklike (Agee 1993; Lehmkuhl et al. 1994; Mutch et al. 1993; Wickman 1992) when trees reached maturity. Outbreaks of mountain pine beetle likely killed patches of ponderosa pine where fires may not have burned for some time, and patches became densely stocked. These disturbances created dead trees, which increased the flammability of these sites. Fire events likely helped enlarge these openings somewhat by killing some of the surrounding trees because the heavy dead fuels helped increase the degree of scorching and injury to nearby live trees. Similar events with respect to Douglas-fir beetle killing groups of Douglas-firs, mountain pine beetle killing extensive areas of mature lodgepole pine, and spruce beetle (*Dendroctonus rufipennis* (Kirby)) killing Engelmann spruce, also occurred. These latter disturbance regimes were probably considerably larger in magnitude--but not as large as today's--compared to the insect outbreaks in ponderosa pine during the same period and likely were followed by stand-replacement fires. Where frequent fires of the presettlement period helped minimize buildup of large fuels and kept stands open, bark beetle epidemics were few and limited in severity compared to bark beetle outbreaks in the overstocked stands of today.

Secondly, the fine fuels that burned frequently in these open stands seldom accumulated to the depths we see in stands today; hence, these presettlement fires were less damaging to trees because flame-lengths generally were low and these fires typically were of short duration by nature of their fuel components. Postfire insect attack is a common occurrence when trees are scorched. Badly scorched trees are more likely to host successful attacks by western pine beetles, mountain pine beetles, red turpentine beetles (*Dendroctonus valens* LeConte), or pine engravers than unscorched or lightly-scorched trees (Fischer 1980; Furniss and Carolin 1977, cited in Agee 1993). Trees were less attractive to beetles after these presettlement fires by virtue of the low degree of severity of their injuries from fire, so large beetle populations most likely did not occur on these areas, except in rare situations. Today, most stands have not burned in many decades, so accumulations of duff and woody fuels are great, leading to more severe fire injuries to trees, and larger populations of beetles drawn to these stands to breed, when they do burn.

Third, open, airy stands maintained by frequent fires during presettlement times contained microclimate conditions that were less suitable for arrestment of bark beetle flight and habitation for brood production. Bartos and Amman (1989), conducting thinning studies in lodgepole pine stands found that thinned stands increased light intensity, wind movement, insolation, and

temperature to levels that were outside the beetle's preferred optimum. Pheromone-baited traps in thinned stands caught fewer beetles (5 percent of the total), than in adjacent unthinned stand, and beetles killed a smaller percentage of trees (2 percent compared to 16 percent) in stands that were thinned. Additional studies (see Bartos and Booth 1994; and Schmid et al. 1995) designed to characterize air and bark temperature, horizontal wind speed, and solar radiation differences in thinned and unthinned stands in relation to stand susceptibility to bark beetle attack have provided more support to the effects of thinning on minimizing bark beetle attack, and by extrapolation the role of fire as a natural thinning agent in creating similar adverse microclimatic conditions for beetles. Fire suppression in the Blue and Wallowa Mountains has disrupted the natural fire-thinning process in stands and has allowed microclimate to become more favorable to bark beetles, thus encouraging beetle attacks, irrespective of tree vigor. Once again, we provide evidence to suggest that frequent fire in the forest ecosystem helped to maintain lower bark beetle populations in presettlement times than in more recent times.

Fourth, patch-size has changed across the landscape as a result of fire exclusion. Patch sizes over any given watershed basin were quite variable in presettlement times. In the drier stand types of the low- and mid-elevation sites, fire-history studies indicate that fire events were frequently repeated over an interval of time (e.g., at least once every decade or two). These disturbances created vegetation patterns with forest stands that were uniformly similar in age and structure. Patches on gently-rolling terrain were large, open, and parklike. In more mesic sites with rapidly-changing topography of differing slopes, aspects, and elevations, patches were smaller, and the landscapes appeared more "quilt-like," broken up by the juxtaposition of different stands. This type of pattern most likely occurred on sites where differing precipitation gradients and rugged mountainous terrain interacted with fire to create mosaics of forest stands of different species compositions and age structures (Camp et al. 1996). These sites had longer fire-return intervals, and forest development moved further along each stand's particular successional pathway, until plant succession was disrupted by disturbance agents including insects, pathogens, and fires of higher intensity than operated in the pine and larch dominated stands growing at lower elevations. Some stands that were surrounded by fire-resistant, early-successional forests with short fire-return intervals, developed to late-successional stages to become fire "refugia" due to a combination of physiography and topography that lengthened the fire-return intervals of those stands (Camp et al. 1996). With over 90 years of fire suppression, coupled with removal of much of the mature and overmature seral overstory tree component, the landscape has been dramatically altered. It now has become more homogeneous, patch sizes have become larger, and patches are fewer; there is less total edge in today's forests than during natural fire cycles (Lehmkuhl et al. 1994). Forest stands have been simplified, but insect and disease host continuity has been increased in the process, leading to increased probability of insect and disease outbreaks, and more rapid spread of pests across the landscape (Lehmkuhl et al. 1994). Fire suppression and timber harvesting practices, in this case, have resulted in a destabilized condition of the ecosystem (see Mason, 1993). We have recently witnessed pandemic infestations of defoliating insects causing widespread tree mortality and damage nearly all across the host type, a spruce beetle outbreak that nearly depleted Engelmann spruce throughout significant portions of the Wallowa

Mountains, and recurring outbreaks of mountain pine beetles, Douglas-fir beetle, fir engravers and others, on a scale possibly unlike anything that occurred prior to the disruption of natural fire cycles. The creation of fuel ladders and large down-woody fuel components by the action of insects and diseases encumbers these stands with conditions ripe for a stand-replacing fire event. Populations of insects--the frequency, severity, and size of outbreaks--clearly have been influenced by vegetation patterns, and patch sizes and densities on the landscape. It is doubtful recent disturbance events by these populations of insects reflect the historic range of variation under natural fire regimes.

These examples conclusively demonstrate how the exclusion of fire from a fire-based ecosystem affects vegetation condition, patch sizes, and patterns across a landscape, and ultimately the behavior of certain insect populations that live within those forests. The vegetation characteristics of any given area on the landscape can only be maintained within its range of natural variation by the natural disturbance regimes that existed prior to European-American settlement, or by some human-created emulation of the effects of those disturbance regimes. Excluding the temporal and spatial effects of these disturbance regimes results in the displacement of seral species by climax species along specific successional pathways. Disruption of disturbance processes, when allowed to occur on a grand scale, over a long period of time, will dramatically alter the appearance and resiliency of the vegetation on the landscape to perturbations by insects, diseases and fires. In short, ecosystem condition will become destabilized. The end results are usually catastrophes (i.e., feedback processes, see Mason, 1993)--widespread insect and disease outbreaks, and large-scale stand-replacement wildfires--unlike any that occurred in presettlement time.

The effects of changes in vegetation composition, structure, pattern, and patch size clearly influence insect populations--whether or not they exceed HRV of presettlement regimes is difficult to say with great confidence since we have so little information about this period. In many cases, they probably do; perhaps in most cases. However, we suggest that probably a better way of looking at current insect disturbance regimes--while we know they may be higher than presettlement regimes--is in terms of where they exist today on a wide spectrum of their biotic potential relative to where they existed in the past. In other words, insect populations respond to their environment by various means. They are capable of responding to changes in their environment through adjustment of numbers and adaptations within the limits set by their biological properties and biotic potential. When environment, including food supply (favorable hosts), is altered by nature or by humans insects adjust their numbers accordingly. If their environment is favorable for survival and growth, and food supply is virtually unlimited, their capability to increase their numbers is limited only by the negative feedback processes in their environment (natural enemies and other mortality factors, both biotic and abiotic), by natural defense mechanism of their host plant, also called "host resistance" (e.g., terpenoids, resin production, oleoresin exudation pressure, etc.), and by their own intrinsic factors that limit their growth, fecundity, physiology, and metabolic processes (i.e., genetic factors). Today's insect activities in forests may be occurring with increased frequency, severity, and over larger areas

than in the presettlement past, but these insects are only operating within an extended range of variability, perfectly within their biotic potential to do so. By our management activities, we have created unstable conditions, and pushed the range of variability and extended it on the upper side from where it was during presettlement times. Most actions of insects, diseases, and stand-replacing fire events generally result in the return of vegetation to earlier seral condition, but this depends on successional pathways and the tree species involved in the disturbance event. When vegetation is outside the natural range of variation of presettlement fire regimes, negative feedback from the system occurs (Mason, 1993). Either insects and diseases respond to these changes and increase their activities and influence on forests, or fire disrupts forest succession at some point in time. If allowed to operate unhindered as natural processes the end result of these disturbance events will usually be the reestablishment of former disturbance regimes that emulate earlier presettlement patterns.

Fire Effects On Conifers

The precise range of host tree fire-injuries to which bark beetles respond is not clearly understood, and likely depends on a myriad of factors--some known, and some unknown. Similarly, the number of factors involved in determining the survival of trees from fire injuries is large. The interactions of these various factors are complex, and not always predictable in the seasons after the burn or fire event, or known before the event. For example, some of the factors that influence the survivability of host trees in the seasons immediately after the burn have to do with the physiological condition of the trees prior to the fire. Some of this information may be observed after the fire, but other factors are less apparent. Trees that have been severely weakened by various factors such as defoliators, root diseases, dwarf mistletoes, moisture stress, and other factors, have less chance of survival after significant injury by fire than healthy, vigorous trees. These weakened trees may succumb to bark beetles in the seasons after a fire, even though they sustained only modest injury from the fire. Multiple stresses on trees, of which fire may be just one of several whose effects are cumulative, greatly increase the chance of an insect outbreak (Agee, 1993). Some level of investigation, other than just simply observations after the fire, may be necessary to determine the relative condition of the stand prior to the fire, that may affect the ability of trees to survive fire injury, or avoid attack by bark beetles.

The measure of resistance a fire-injured tree possesses determines the ability of the tree to avoid beetle-related mortality several seasons after a burn. The injured tree's ability to produce stem-wood and defensive chemicals to protect itself against insects and diseases is severely restricted after a disturbance to its physiological makeup. This is because most of the carbon produced during photosynthesis is allocated to repair injured tissues. Production of new replacement foliage in the crown and regrowth of damaged root tissues take precedence over bole-wood and defensive chemicals in the carbon allocation hierarchy within a tree (Waring and Schlesinger, 1985; Waring and Pitman, 1985). Production of defensive chemicals is very costly to the impaired energy budget of fire-injured trees; hence these trees are fairly easy prey for

phytophagous insects.

Conifers differ in natural susceptibility to bark beetles by species. Bark beetle activity in some conifer species are not of great concern after a fire because the tree is not susceptible to any of the major tree-killing species. In other cases, bark beetles are not known to build up large populations in certain fire-injured conifers and subsequently spread to uninjured trees in nearby stands, even though these conifers are primary hosts for those bark beetles. Some conifers such as western larch, for example, are not attractive to any major tree-killing bark beetle species in the Blue and Wallowa Mountains, but they are attractive to some of the woodborers of the families Cerambycidae and Buprestidae and other secondary insects like ambrosia beetles, when injured by fire. Attacks by these insects are usually sublethal unless they occur in such high numbers that they eventually overcome the tree's defenses. Such instances are rare.

Certain conifers such as the true firs (grand fir, white fir, and subalpine fir), Engelmann spruce, and occasionally lodgepole pine (local experience has shown that lodgepole pine has a high probability of being killed by fire) are readily killed by even light ground fires, which may or may not be an objective of the project burn. These trees may sustain damage to shallow root systems, or bear unapparent damage to phloem or cambium. True fir saplings up to 4 inches in diameter breast height (dbh) have photosynthetically active bark that is easily killed by radiant or convective heat from a fire (Hall 1976). Still, other trees may have cambium killed from heating or scorching of bark, and foliage and buds may be killed by heating or scorching of the crown. Trees with dead cambium cannot support bark beetle broods; these trees are usually not attacked by bark beetles. White fir or grand fir are somewhat anomalies in that individual trees of small and medium sawlog diameters are readily killed by even "light" fire injuries due to their shallow rooting habit and thin bark. This fire-sensitivity of true firs explains the scarcity, or lack of these species in the historic open parklike seral stands reported by early settlers in many areas of the Blues. However, as these trees mature they develop thicker bark that insulates the cambium and increases their survivability to light-, and perhaps some moderate-intensity surface fires. In dry habitat types such as ponderosa pine plant associations, and other dry associations where ground fires had historically short fire-return intervals, one occasionally finds an overmature fire-scarred white or grand fir that managed to avoid lethal injuries from earlier fire events during its lifespan due to thick bark insulating the cambium from damage. Often these remnants are living records of previous fires and exist as wildlife habitat for a variety of animal species.

Effects of Seasonality on Survival of Fire-injured Conifers

As more prescribed landscape underburns are being planned and implemented, the season, or time of year that burning is conducted, must also be a consideration when assessing fire effects on conifers. Studies and observations from both prescribed burns and wildfires occurring at different times of the year are helpful in understanding the influence of season on a tree's ability to survive injury from fire. For example, from studies of 30 burns on 12 National Forests in California and in Yosemite National Park, Wagener (1961) generalized that damage was most severe during

active tree growth early in the season. Trees were better adapted to withstand fire injuries from late-season fires, when growth had slowed. Bud kill was more important than foliage kill in ponderosa pine and jeffrey pine based on Wagener's studies. However, he found injuries to buds and foliage in Douglas-fir to be nearly equal in importance to the post-fire survival of that species. From an insect-risk standpoint, however, tree injuries from the early-season fires increase the susceptibility of these trees to insects just as the adult beetle populations begin flying in spring or early summer. Insects can colonize the freshly fire-injured host trees all summer long under this situation, and begin building large populations that could lead to outbreaks. Late season fires, on the other hand, typically occur after most of the bark beetles have already flown and colonized hosts, so trees injured at this time may not be colonized by beetles until the following season. This is an important consideration both in the timing of salvage in the wildfire situation, as well as for avoiding outbreaks of bark beetles in the prescribed landscape underburn situation where salvage of fire-injured trees is not an objective of the project.

Studies conducted on prescribed fires have also provided additional support to the generalizations on seasonal effects on fire-injured conifers that were based on natural fire events. Crown scorch mortality of ponderosa pine in Colorado after spring, summer, and fall prescribed fires was investigated by Harrington (1987). He found that after 5 years, 12% of the trees scorched in the fall had died. This compared with 26% mortality among trees scorched in spring and 29% mortality of those scorched in summer. Fires early in the growing season cause more damage from lethal heating of buds, affecting a tree's capability to photosynthesize, than compared to late-growing season or dormant season fires. A diminished capacity to photosynthesize will also reduce a tree's ability to resist insect and disease damage. Ponderosa pine has been found to be most vulnerable to fire damage during the growing season (Sutherland 1987).

The warm, dry ponderosa pine plant community has evolved with the hot, dry summer climate typical of the Intermountain West. By mid to late summer, when moisture becomes significantly limiting, seasonal shoot growth ceases and ponderosa pine begins initiating the physiological processes that induce predormancy (Kramer and Kozlowski 1979). Plants that have moved into a predormancy state still have a capacity for growth, but the range of environmental conditions in which they can grow becomes narrower. As conditions become less favorable to active growth, dormancy continues to deepen until true dormancy is attained and shoots cannot elongate even under the most favorable environmental conditions. Dormancy can be induced in most plants by altering temperatures, day length, light quality, availability of nutrients, or water supply. Ponderosa pine is a species where predormancy is more influenced by water availability than by shortening day length. Usually by late summer, ponderosa pine trees are shutting down, growth ceases, and bud set is initiated.

Few studies have been conducted to compare the effects of spring, summer, and fall prescribed underburning. As we attempt to put more fire back into our fire-dependent ecosystems in the

Blue Mountains, more site-specific, local knowledge regarding the effects seasonality of burn can have on tree survival is badly needed. At one time, frequent, late summer or fall ignited fires of low-intensity could burn along the forest floor through an open, parklike stand with minimal effects to the survival of large overstory ponderosa pine, or even younger-aged trees (fig. 2.). Today, there are increased risks of mortality to even the largest, fire-adapted trees now that forest conditions are well outside the historic range of variability. There are thick accumulations of old, highly flammable pine needles and bark flakes around the base of large, old trees that would have historically been burned off every 5-10 years. There are greater densities of small diameter, shade-tolerant, less fire-resistant species comprising a multi-storied stand structure that provides a "ladder" into the crowns of the overstory. There are increased fuel loads caused by drought, insects, and disease in stands stressed by competition for limited water and nutrients. When comparing and attempting to weigh the effects of spring versus fall burning, one must keep in mind that the composition and structure of our forested landscapes here in the Blue Mountains, especially in the ponderosa pine and warm, dry mixed conifer ecosystems, are no longer as they were when these fire-adapted ecosystems were dynamically stable, resilient, and resistant to fire. Years of fire suppression and selective harvesting of seral species have changed the complexion of these landscapes.

Root Damage

Fig. 2. Ponderosa pine stands containing light accumulations of fine fuels, such as this stand contained before the fire, can underburn with minimal damage to trees.

Effects on roots from prescribed and wild fires have been only partially studied compared to above-ground tree damage (Agee 1993). Fine roots having small diameters and thin bark are more easily damaged by fire than larger diameter roots containing thicker bark covering root cambium. Conifers with shallow-rooted habits, such as the true firs and Engelmann spruce, frequently sustain damage to roots from surface fires. Fire-weakening of roots, especially in subalpine fir and Engelmann spruce, reduces root structure integrity, anchoring, and wind firmness. These conditions often lead to blowdown of these trees during severe windstorms. On the other hand, conifer species possessing deep rooting characteristics such as ponderosa pine, lodgepole pine, western larch, and Douglas-fir are usually not often root-damaged by underburns. However, when fire frequencies have lengthened and accumulations of duff have developed, fine roots and small diameter root systems are often in close proximity to the mineral soil surface. Damage to fine roots from low-intensity underburns have been associated with both growth reductions in young ponderosa pine stands (Grier 1989, cited in Agee, 1993), and, with tree mortality in low vigor, old-growth ponderosa pine stands

(Swezy and Agee 1991, cited in Agee 1993). Grier (1989) conducted a study of the effects of early-season fuel reduction underburning on primary production and nutrient cycling in 45-year-old ponderosa pine stands. While ponderosa pine is a fire-adapted species, it is adapted to fires occurring late in the growing season, at least in the Intermountain region. Grier found that early season fires are most damaging when roots are actively growing; heat conducted into the soil during early season fires may damage or kill roots, consequently reducing productivity. The combination of moist soils with their ability to readily conduct heat and the low soil temperatures to which roots are adapted after winter, amplifies these heat effects. During late summer or early fall fires, roots are largely inactive, soils are dry and thus good insulators, and roots are adapted to higher soil temperatures (Grier 1989). Large, old-growth trees are often physiologically less vigorous due to their age (Kramer and Kozloski 1979). As a tree increases in size and builds up a complex branch system, it shows a decrease in metabolism, gradual reduction in growth of vegetative and reproductive tissues, loss of apical dominance, increase in dead branches, slow wound healing, and an increased susceptibility to injury from insects, diseases and unfavorable environmental conditions. The recovery and subsequent growth of a fire-damaged tree is a function of the tree's capacity to carry out major physiological processes, especially photosynthesis. The additional stress from fire-incurred root damage, just when budburst is taking place and the active growth period is beginning, may be in excess to what these large, older trees can tolerate. Spring burning occurs during the most active growing period for many plants. The ability of a plant to recover from damage decreases because carbohydrate reserves are lowest at this time.

Prescribed fires that burn with high intensity and long residence time can cause serious damage to the soil and root systems of trees. These fires may injure or kill roots of even deep-rooted tree species, including some individuals that initially survive the fire. Spring burning may produce cooler burns, but where large, old-growth ponderosa pines have a significant buildup of needle mass around their base, duration of burn may be long enough to, in effect, "cook" the root crown. Sackett (1987) presents evidence that cambial and root damage may be significant for old ponderosa pine trees where there is a large accumulation of old needles and bark flakes at the base of the tree. Intense heat is created when fires burn in deep layers (2 to 8 inches) of forest floor material concentrated around old trees. Only the surface forest floor layers may burn as flaming combustion, but glowing combustion consumes most, if not all, the duff during the remainder of the fire activity. As the fire burns down through the forest floor, an insulating ash layer forms which keeps heat from escaping. As a result, soil temperature is elevated, soil moisture is reduced or driven downward, and cambium temperature is increased. Trees with severe damage to root systems may subsequently die from these injuries within a few years after the fire. Swezy and Agee (1991) suggest that live-root mortality results in prolonged stress associated with decreased radial growth and increased susceptibility to insects. Often severe root damage to conifers by certain types of fires are deceptively subtle. For example, a low-intensity ground fire through stands with grand fir, white fir, or subalpine fir frequently produces no visible injury to the bole or the crown, except for a low ring of blackened bark near the surface of the ground where the duff layer burned up against the bole of the tree. These trees have green

crowns and appear to be alive. They seem to have survived the fire. However, the prospect of these trees surviving more than a few seasons after the fire is relatively poor. In our experience these shallow-rooted conifers, more often than not, have received moderate to severe damage to roots by fire and usually succumb in subsequent years.

In the forests of the Blue and Wallowa Mountains where successful fire exclusion has been the only acceptable form of fire management, a thick duff layer has accumulated. Smoldering of the duff layer may persist many hours after the fire front has passed (Agee 1973). The combustion of this duff results in temperatures exceeding 500°C. These temperatures can readily kill cambial tissues insulated by the bark (Ryan and Frandsen 1991, cited in Agee 1993) and fine roots insulated by the soil (Grier 1989; Swezy and Agee 1991, cited in Agee 1993) when these smoldering-duff temperatures persist several hours and these temperatures are at rooting depths. Roots that are killed, or if enough of them are severely damaged, will lead to the tree's death either directly from fire injuries, or indirectly from bark beetles (e.g., fir engraver in fire-injured true firs and spruce beetle in fire-injured Engelmann spruce). These bark beetles can be attracted to the fire-weakened trees in the seasons after the burn.

When true firs incur root damage from smoldering duff as described above, or by long-duration burning of large woody fuels over root systems, yet show little or no signs of bole or crown injuries (although the phloem has been dried out), they may still have functioning xylem taking water to the crown, but non-functioning phloem, thereby preventing the return of carbohydrates to the lower bole and roots. Oftentimes the blackened ring around the base of the tree has resulted in complete girdling of the phloem of the tree or killing the cambium all around the bole at this location. Trees injured in this manner, though they may appear to be alive with green crowns are unable to make needed repairs to root tissues damaged by fire, and eventually succumb to these injuries.

Ryan (1988) considers the root crown to be part of the broader root system of trees. His **preliminary** work indicated that generally, in the absence of significant tree crown injury, most trees survive up to 25 percent of the root crown base girdled by fire, but few trees survive more than 75 percent of root crown basal girdling. His research indicated that between these ranges about one-half of the trees survive. Shallow-rooted trees most likely experience higher mortality rates due to hidden root injuries associated with the higher levels of fire damage that cause root, or root-crown girdling.

Fire-injured roots predispose some trees to root infections by fungi. Gradual weakening of the tree from chronic stress eventually leads to increased susceptibility to insects and eventual tree death from bark beetle attacks (Gara et al., 1985; Littke and Gara, 1986). Root-diseased trees that sustain fire injuries to fine surface roots can undergo moisture stress, windthrow, or mortality (Stewart and Hagle, 1988).

Crown Damage

Fire can affect foliage in the crown in several ways. Complete consumption of foliage may occur during high-intensity single tree or group torching. Partial or complete scorching or browning of foliage may occur over portions of the crown, leaving the remainder of the crown green and uninjured by the fire. Scorched crowns of ponderosa pine may also bear branches with scorched or heat-injured foliage containing green needle bases; an indication that surrounding parts of the crown are still alive (Wagener, 1961). Sometimes foliage of scorched crowns become "frozen" in place in the direction of the movement of the fire by hot air and combustion gases that sweep past the tree crown (fig. 3.).

Superheating of air by convection from the fire and exposure to hot gases from combustion causes foliage on live branches (especially noticeable on ponderosa pine) to turn a dull green color. This foliage is dead and usually stands or hangs in a normal position (Wagener, 1961). However, it does not necessarily mean that the twigs on which these needles occur are also dead. Close examination of the buds on branches of large resinous-bud species like ponderosa pine frequently reveal live buds with green succulent tissues within (fig. 4.).

Needle length and distribution of foliage along twigs are important characteristics in protecting both buds and the twigs on which they are attached from fire. Ponderosa pine contains long needles that help shield buds from heat during a fire. In addition, the arrangement of needles on the twig helps provide some protection from heat injury to the cambium beneath the bark of these structures. Heavily scaled buds of ponderosa pine are another adaptation that helps protect live tissues within from fire. This is a significant resistor trait (see Agee 1993) that contributed to the establishment of this species in the fire-prone environment of much of the interior west. These types of protective adaptations are not afforded most other conifer species in the Blue and Wallowa Mountains; their crowns are more easily injured by fire as a consequence. When the root and bole cambium are still alive on ponderosa pines with heat-injured foliage, which often they are, these trees have a greater chance than most other fire-injured conifers of surviving the fire.

By spring of the year after a prescribed burn, twigs with heat-killed or scorched foliage that are still alive will have dropped most, or all of the dead needles, and will produce new green needles from the live buds on these twigs; whereas, twigs that are dead will continue to retain the dead needles (Wagener 1961). Ponderosa pines with heat-killed or scorched foliage begin shedding dead needles from live twigs within a month or so after the fire. After a few months, crowns of these trees begin to appear somewhat thin from this defoliation. An abundance of needles invariably accumulates beneath these trees. Much fewer needles are found beneath trees with more persistent dead needles on dead twigs. However, this is not always a reliable means of identifying living portions of the crowns, although it may be somewhat helpful when used with other indicators. The only positive way we know to determine the amount of live crown present within a short time after the fire is to check for green buds, green-based needles, live twig

cambium, and bole cambium, especially near ground level. Conifers with small or slender buds such as true firs, spruce, and Douglas-fir are much more subject to fire-related crown injuries resulting in bud killing than species with large resinous buds like ponderosa pine. As a general observation, Ryan (1988) states that the death of dormant buds of ponderosa pine, lodgepole pine, western white pine, and western larch occurs at about a 20 percent lower height than foliage. This observation may be somewhat useful when considered along with other criteria in determining survivability of trees.

Fig. 3. Scorched ponderosa pine foliage "frozen" in place in the direction of the fire movement by superheated air and hot combustion gases from the fire.

Fig. 4. Foliage-scorch on large resinous-bud conifer species like ponderosa pine does not always indicate crown mortality. Frequently, the buds of these species were protected by thick bud scales and by surrounding foliage from lethal temperatures. Dissection of these buds often reveals healthy green tissues within.

Crown damage is most severe in spring and early summer burning due to the low foliar moisture content and the succulent nature of the buds and twigs (Wagener 1961). Bark beetles have been able to concentrate on damaged trees after early season burns. After dormant season burns, insects cannot respond to the stressed conditions of damaged trees until spring, which allows surviving trees additional recovery time (Miller and Keen 1960).

From an entomological standpoint, the real biological significance of crown damage by fire is related to the impact on growth and vigor of individual trees. Studies reported by Miller and Keen (1960) clearly showed that the susceptibility of crown-injured ponderosa pines to western pine beetle (*D. brevicomis*) attack were associated with fire-caused suppression of growth

corresponding to crown injury and defoliation. These effects are duplicated in other conifer species after crown injury by fire; they also similarly become attractive to their bark beetle predators after these injuries. In other studies, pre-burn stand densities and the resulting growth rates prior to underburning in ponderosa pine stands continued to affect the post-burn growth rates at the same rate two years after burning (Sutherland and others, 1991). That is, if the tree was growing well before the fire, it resumed this rate two years after the burn. Slow growth resulting from high stand densities also resulted in a continuation of that pattern after the two year period. High stand densities have also been correlated with severe beetle attacks (Dolph 1982; Eaton 1941; Sartwell 1971; Sartwell and Dolph 1976; Sartwell and Stevens 1975; and Schmid and Mata 1992).

Cambium Damage

Cambium damage from surface fires or underburns is often variable around the bole of trees. This is because the distribution of heat around the tree bole is rarely uniform (Agee 1993). Fire scars or "cat faces" on old trees are the most familiar examples of heat distribution effects from fires on bole and cambium. For all plant tissue, whether needle, root, bud, or cambial, lethal temperatures vary with the duration of exposure. High temperatures for short periods or lower temperatures for prolonged periods of time can have similar results. Fire duration is the factor most responsible for injuries to the bole during fires (Ryan 1988). Fires of long duration, and under conditions where moderate to high levels of fuels have accumulated around trees are most likely to cause bole charring and kill most, or all of the cambium some length up the bole, or around the entire circumference of the bole. To survive a fire, plant tissue needs to either be distant from the heat source or well insulated from the heat (Saveland and Neuenschwander 1989).

A number of factors are involved in determining the vulnerability of cambial tissue to fire injury in individual trees, but bark thickness is believed to be the most important physical characteristic that determines how well a tree protects the cambium from fire (Martin, 1963; Reifsnyder et al., 1967; Uhl and Kauffman, 1990, cited in Agee 1993). Bark thickness of conifers varies with species, age, and location on the stem. Starker (1934) classified several conifer species of Oregon and Washington as to their relative fire resistance. Bark thickness of old trees was one of the criteria he addressed in his classification. Species with **very thick** bark included western larch, ponderosa pine, and Douglas-fir. These are the three most fire resistant species in the Blue and Wallowa Mountains. He considered old trees of white and grand fir to possess **moderately thick** bark. The bark in these older-aged true firs enables them to survive repeated surface fires, like their more shade-intolerant neighbors with thicker bark. Younger-aged white and grand firs have thinner bark and are more prone to cambial injuries from fire as a result. Lodgepole pine, Engelmann spruce, and subalpine fir all contain **very thin** bark, which explains in part why these species are so often killed by fires, regardless of their age or diameter.

An equation has been developed (Peterson and Ryan, 1986), based on bark thickness, to

determine the critical time required for cambial kill as a function of tree diameter and species, at a fire temperature of 500°C. Bark, however, is not uniformly thick around the bole, and depending on species and age of the tree may be quite furrowed or fissured. The deep fissures contain younger and thinner bark over the cambium, and often have a higher probability of cambial kill in narrow bands beneath these fissures (Agee, 1993). This suggests that in thick-bark species like Douglas-fir, these deep fissures are likely places for repeated cambial kill along the same bole radius, from periodic fires (Agee, 1993). These injuries, that appear as narrow strips of brown, dead cambium and wood underneath the deep bark crevices on the lee side of the tree are the most common form of cambial or inner bark injury, and ordinarily have little influence on tree survival (Wagener, 1961).

The amount of cambium killed, and condition of the inner bark on the bole of the tree are important factors determining the susceptibility of fire-injured trees to beetles. Bark beetles will not attack and produce brood in areas of the bole where the cambium has been killed; hence, the tree will be attractive to, and provide suitable habitat for beetles only if it still contains patches or strips of live cambium. Miller and Keen (1960) report that the conditions favorable to brood development in fire-injured ponderosa pines are highly variable in different burns. Bark beetles must produce high natality and brood survival rates as they develop under the bark in order to increase numbers and continue to exploit habitat created by fires. Brood success is directly related to causes of epidemics that develop in burns (Miller and Keen, 1960). Beetles that are not pitched out of fire-weakened trees may initially produce a brood, but conditions sometimes develop that become deleterious to the brood, such as pitch flowing into larval mines or increasing moisture in inner bark and sapwood. Miller and Patterson (1927), for example, noted high mortality of western pine beetle broods in fire-scorched ponderosa pine whenever inner bark became extremely moist from the physiological changes occurring in these trees. They noted that much of the moisture in the sapwood and cambium apparently condensed in the inner bark of these trees, resulting in highly unfavorable conditions to the young beetle larvae.

The texture, appearance, and sometimes smell of cambium can be used to determine its viability in fire-injured trees. The cambium of trees that is pinkish- or whitish-colored when healthy typically becomes darker, and possesses a dry texture, when killed by fire. As microorganisms begin to break down carbohydrates in the fire-damaged cambium and phloem, these bark components begin to sour and sometimes take on a detectable fermentation-like odor. Fire-weakened ponderosa pines frequently host red turpentine beetles (*Dendroctonus valens* LeConte) which attack the lower tree trunk, root crown, and sometimes main roots below ground. Bark beetles of the genus *Hylurgops* are attracted to fire-killed ponderosa pine, lodgepole pine, and western white pine in the Blue and Wallowa Mountains due to physiochemical changes in the inner bark. For example, *Hylurgops subcostulatus* (Mannerheim), known as "sour sap" beetles are attracted to fire-killed trees once fermentation products develop as metabolic by-products of microbial activity, and breakdown of carbohydrates occurs in the wet phloem and cambium at

the base of the trunk, root crown, or in the main roots after fire injury (Furniss and Carolin 1977; Keen 1952).

Wagener (1961) notes that concentrated resin flow from specific areas of bark or exposed wood indicates that cambium has been killed underneath. In some species where the cambium has been killed by fire, resin will concentrate at the sapwood/cambium interface yielding a sticky surface between these layers when they are separated. This is particularly evident in fire-killed cambium on western larch.

Aside from becoming attractive to bark beetles, trees with fire-injured boles that expose sapwood may also provide an opening on the bole that promotes colonization by fungi. These trees, initially weakened by fire, may continue to decline over time and eventually be killed by beetles many years after the fire. Geiszler et al. (1980) reported an interesting relationship between fire, fungi, and beetles in lodgepole pine in south-central Oregon. They found that Schweinitzii root and butt rot (*Phaeolus schweinitzii* (Fr.) Pat.) colonized older, fire-surviving lodgepole pine through fire scars, after fires swept through lodgepole stands killed by mountain pine beetle. After 30-100 years, the fungus developed to an advanced stage of decay, and reduced the tree's resistance to bark beetles. This resulted in another mountain pine beetle epidemic in the residual trees. Though trees may survive the fire, and initially escape colonization by tree-killing bark beetles, non-lethal attacks may occur by other insects and eventually their weakened condition may predispose them to organisms that gradually bring about their death decades later. The red turpentine beetle plays an important role in this process as it commonly attacks conifers soon after fire. It is most common on ponderosa pine but occurs on other conifers, as well. The insect rarely causes direct tree mortality, but rather, gradually weakens trees by attacking and killing small patches of cambium on the lower bole, in the root crown area, and in larger roots below ground. Over many year's of these infestations, the weakened tree eventually becomes attractive to other bark beetles and succumbs to their attacks.

Bole injuries from fire can also have subtle physiological effects on the tree's growth and ultimate survival some years later. Fire injuries to the bole seriously disrupt processes of transport and storage of water, nutrients, carbohydrates, resins, and terpenes (Ryan, 1988). Carbohydrate flow to the roots is especially impaired when large areas of bole cambium are killed by fire. Impairment of carbohydrate transport disrupts production of fine roots; thereby leading to moisture stress (Ryan, 1988). Severe moisture stress may directly cause tree mortality, or may result in these trees subsequently being attacked and killed by bark beetles.

In addition, some evidence exists that stem water storage capacity may be reduced as a result of increased sapwood xylem transport resistance associated with resinosis and subsequent sapwood deterioration in fire-injured stems (Ryan, 1988). Under extreme conditions, these basal injuries and destruction of active xylem tissue can lead to severe moisture stress, especially in the upper crown, resulting in physiological injuries such as topkill (Rundel, 1973). The degree of cambial

injury in fire-scorched boles is difficult to assess. Studies have not been definitive in quantifying cambial injuries or correlating external damage with cambial death. Wagener (1961) suggests that a tree's survival chances are reduced when cambium in more than one-fourth of the circumference above stump height is injured. In most trees, removal of portions of outer bark from each quadrant at this height is diagnostic in determining amount of surviving cambium. However, some individuals have reported--and we have also confirmed by observation--cases of ponderosa pine mortality in approximately 12- to over 20-inch (dbh) bole-scorched trees in which the cambium above stump height appears alive, but the cambium **all** around the base at ground level was dead. Apparently, fire either smoldered in the thick organic duff with long residence times, or heavy woody fuels burned close to the bole for long durations, girdling the bole. These trees had a characteristic ring of deep bark charring around the base of the bole at about ground level, and more typical surficial charring of bark above this location. Clearly, the longer the bark is heated and in contact with the flaming edge of a fire, the greater the reduction of bark layers insulating the cambium, and the higher the probability of cambial damage or death. Heat injury to the cambium around the root collar was found to be important in the selection of these trees by bark beetles (Rust, 1933; cited in Miller and Keen, 1960). On the other hand, considering just the influence of fire-injury alone, both Wagener (1961) and Ryan (1988) suggest that cambial injury that occurs higher on the stem is more critical to tree survival than similar injuries lower on the stem, though neither were able to explain why. Therefore, caution should be used in interpreting expected cambium damage from external observations of bole scorch.

Ryan (1988) stated as a general rule that cambium injury should not exceed one quadrant of the bole circumference if high tree survival is desired. Although this is probably reasonable, we suggest that when insect risk is factored in for certain species, certainly a rule of "less is best" applies. For example, even relatively light bole injuries in Douglas-fir when associated with small volumes of crown scorch can still be moderately attractive to Douglas-fir beetles (Furniss, 1965), especially if beetle populations were abnormally high before the fire.

Guidelines and Indicators to Assess Fire Severity and Potential for Insect-caused Mortality

Based on numerous fire studies, Miller and Keen (1960) concluded that most fires have not evoked major outbreaks of bark beetles in the pine types. Nearly all natural fires attract bark beetles at some level to fire-injured trees. Depending on a number of factors, some populations of beetles attracted to fires do become outbreaks. Douglas-fir beetles seem to be more readily attracted to nearly all degrees of fire injury, and this complicates the problem of determining the survivability of fire-injured Douglas-firs (Furniss 1965). Fires that occur in areas having abnormally high beetle populations prior to the fire certainly have the potential of permitting beetle populations to increase to outbreak, and bear monitoring. We have observed approximately 10-22 inch (dbh) ponderosa pines, with moderate to severe injuries from wildfires that occurred in late July-early August, that were colonized by mountain pine beetles and

western pine beetles soon after the fire, while younger, severely-injured pole-size pines were attacked by pine engraver beetles on different portions of the same fire (i.e., Elkhorn Fire). The extent to which these insects might increase and spread to other fire-injured trees or green stands nearby is difficult to say, but some increase and spread are probable.

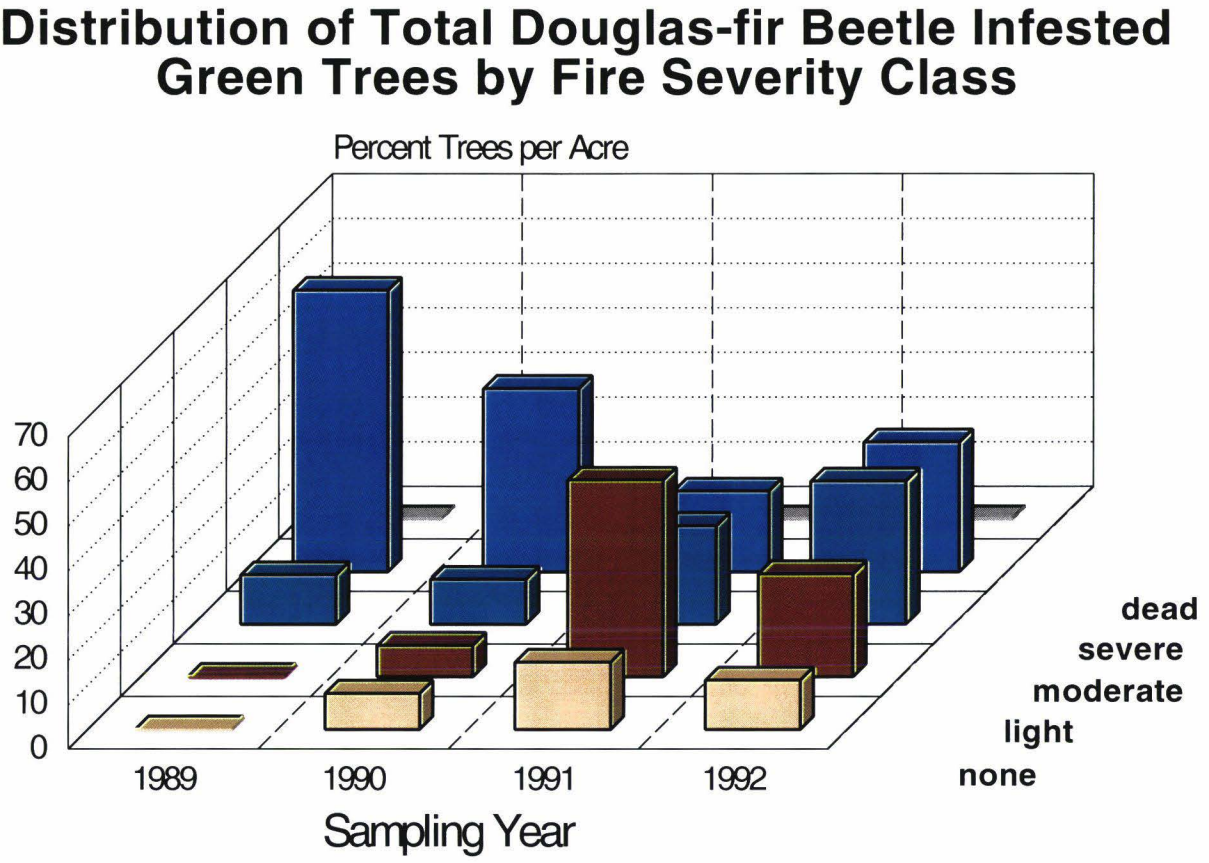
Douglas-firs injured during wildfires apparently have a higher probability of supporting outbreaks of Douglas-fir beetle than the fire-injured pines based on our local experience. The Tillamook Fire of 1933 in western Oregon is an often cited example of fire-injured trees inciting an outbreak of beetles after the fire. This large fire that killed and injured significant numbers of mature and overmature Douglas-fir promoted a major outbreak of Douglas-fir beetle over a 5-county area, producing significant tree mortality from the beetle alone (Bedard 1950). We have frequently observed that large-diameter Douglas-fir with moderate to severe injury from fire are invariably attacked by Douglas-fir beetles after the fire (fig. 5). Douglas-fir beetle populations have remained higher than normal for several years due to widespread weakening of host trees from recent defoliators and drought-stress events, and from a series of annual fires that continues to provide ample breeding habitat each year for beetles. We have observed populations of Douglas-fir beetles increase on several recent wildfires in northeastern Oregon in both natural fires (i.e., Tepee Butte, Joseph Canyon, Pumpkin Ridge, Twin Lakes, and Bull Fires), and prescribed landscape underburns (i.e., Wapiti). Fire-injured Engelmann spruce also have the potential of drawing large numbers of spruce beetles into fire-injured stands. Spruce beetles have been observed exploiting fire-injured habitat on at least one recent lightning-ignited fire on the Malheur National Forest (i.e., Sunrise Fire). Surviving fire-injured spruce were killed by spruce beetle populations that were drawn to these trees from surrounding green stands containing Engelmann spruce, after the fire.

Fig. 5. Mature Douglas-firs with bole scorch from fires are frequently attacked by Douglas-fir beetles soon after the fire. Trees attacked by bark beetles can be recognized by the presence of reddish-brown boring dust in the bark crevices. Although difficult to see, this tree contains fresh boring dust from Douglas-fir beetle attacks.

After the Tepee Butte Fire of 1988, it became apparent that local concerns were high that bark beetles might be attracted to fire-injured trees, build up large populations, and spread into

adjacent uninjured commercial stands of timber. The Wallowa-Whitman National Forest decided that bark beetle monitoring on this fire was prudent and necessary to detect increasing populations and react to any potential outbreaks. A subsequent review of the literature helped to establish several fire rating criteria that were important factors in the susceptibility of fire-injured conifer trees to insects. Coupled with our own field observations on insect behavior after wildfires, we modified existing fire-effects criteria by Wagener (1961) to develop a set of visual fire effects indicators that centered around bole and crown injuries, into what we called "burn-severity guidelines," for the purpose of monitoring insect activity after wildfires. Wagener's guidelines helped estimate survival of fire-damaged tree species in California, but didn't address the potential for insect attack except in a cursory way. Our modifications incorporated factors of susceptibility of fire-injured trees to bark beetle attack into Wagener's guidelines. Preliminary assessment of bark beetle monitoring data from the Tepee Butte Fire (fig. 6) and several other large wildfires in northeast Oregon revealed that the burn-severity guidelines--though quite simplistic--could be used with relative success in identifying the approximate range of injuries to certain conifers that make them attractive to bark beetles. These guidelines, then, have been used to monitor several wildfires in the Blue and Wallowa Mountains since their development in 1988-89. Since it was possible to link bark beetle infestation patterns to burn severity levels observed in Douglas-fir (fig. 6) and ponderosa pine, these guidelines eventually evolved to become part of the marking guides for some of the past fire-salvage operations in the Blue and Wallowa Mountains.

We are now attempting to move these guidelines beyond the mortality prediction application--the salvage sale realm that exists after wildfire--to a prescribed fire application, where they may be useful in developing landscape underburn prescriptions. Since the prospect exists for bark beetles to build up populations and *potentially* become epidemic in an area after a prescribed fire, it would be useful to have a simple and quick way of gauging the significance of fire injuries to attracting hazardous numbers of insects to the injured trees surviving on a burn, as well as being able to use this information in helping to develop underburn prescriptions. The original burn-severity guidelines categorize fire injuries of Inland conifers into three classes, with particular reference to ponderosa pine and Douglas-fir. In most cases, these are the major species of concern from an entomological standpoint in the Blue and Wallowa Mountains. Recent fire-effects studies were either after wildfires or on prescribed burns. These studies, and additional years of local experience have combined to bring other modifications to the burn-severity guidelines and broaden their application. For example, they now contain high, moderate, and low insect or fire "risk" components under each of the three burn-severity classes. The guidelines and visual fire effects indicators presented here can help resource managers determine the survivability of trees from both fire and insects in the first few years after the prescribed fire, and help to quantify the risk potential for insect infestations. Obviously, endemic insect population levels affect tree mortality rates after fire. Unanticipated, abnormally high beetle populations within close proximity to a burn may result in higher levels of infestation than what might be expected based on the guidelines. The additional modifications that have been made to the guidelines take into account some of the present-day, as well as older research



ɔee Butte Fire, Wallowa-Whitman National Forest

Fig. 6. Infestation patterns from 1989 through 1992 of Douglas-fir beetles in fire-injured Douglas-fir on the Tepee Butte Fire, by burn severity class. Fire occurred August 25, 1988. (Source: Unpublished data by D. Scott).

findings on fire-related tree mortality. Other changes may be made eventually, after a complete analysis of the earlier monitoring data is available, and as new information from additional studies evolve. The main thrust has been to develop first- and second-order fire effects visual indicators that, while we know are not absolutely accurate, at least provide resource managers with a reasonably easy-to-use tool to assess the relative survivability of fire-injured trees in an expedient manner, while still leaving room for individual interpretation based on professional judgement. The fire effects visual indicators should be useful to assess potential tree mortality due to insect attacks on fire-injured trees, or fire-related mortality in the fire-based ecosystems of the Blue and Wallowa Mountains, and perhaps elsewhere.

The current fire effects indicators are incorporated in two tables (see tables 1 and 2). Table 1 contains the burn-severity indicators for determining risk of fire- and insect-related tree mortality in ponderosa pine, Douglas-fir, and Engelmann spruce host trees. We consider these three tree species to be the major species having the greatest potential of developing large tree-killing populations of bark beetles in the Blue and Wallowa Mountains in fire-injured trees. Of the other major conifer species occurring here (western larch, lodgepole pine, grand fir/white fir,

and subalpine fir), only lodgepole pine supports what we consider to be a major tree-killing bark beetle species: mountain pine beetle. However, most lodgepole pines of the age and size susceptible to mountain pine beetles have been killed in earlier bark beetle outbreaks in the Blue and Wallowa Mountains (see Gast et al. 1991); hence, the residual mixed conifer and pure lodgepole pine stands involved in present day fires generally contain smaller-diameter lodgepole pines that are at lower risk to mountain pine beetles after a fire, than are larger diameter trees. Additionally, these trees may be attractive to pine engraver beetles (Geiszler et al., 1984), but outbreaks of this insect are usually not long-termed, nor serious enough to be of great concern. For these reasons, lodgepole pine has been placed in Table 2, along with the other species that are considered to have primary risk from fire-related mortality only, rather than from fire- and insect-related risks.

The values listed in the following tables can be used with the outputs from more robust fire effects prediction models such as: First Order Fire Effects Model (FOFEM) (Reinhardt 1993), or BEHAVE (Fire Behavior Research Work Unit, Intermountain Fire Sciences Laboratory, Missoula, MT) and the subsystems that function as a part of it. These models will help with mortality predictions as they relate to scorch and flame lengths. Flame length predictions that can be derived from these models will provide potential relationships to bole charring.

For those familiar with the fire effects literature, we will define certain terms used in the tables that follow to avoid confusion over potential differences in fire effects terminology used in the literature. **Crown Volume Scorch** is a visual estimate of the percentage of the prefire crown volume (comprised of foliage and buds) that is killed by the fire. **Scorch** is a general term that means "to burn slightly; char and discolor the surface of" (Guralnik and Friend 1966). **Basal Scorch** refers to the percent of circumference of the bole charred to the stated height on the bole above ground line. **Bark Charring** is the blackening of the bark to some depth of the bark, such that ash is present (as opposed to superficial blackening of the bark surface that might result from low-intensity fires or flash exposure to flames). Bark charring implies a degree of penetration of heat into the bark and potential for dead cambium.

Table 1. Insect mortality risk considerations for selected conifer species based on first- and second-order fire effects visual indicators.

Burn Severity	Beetle- and Fire-Mortality Risk	Ponderosa Pine[1]		Douglas-fir[1]		Engelmann Spruce[2]	
		% Crown Volume Scorched (% green buds & needle bases[3])	% Bole Scorch[4]	% Crown Volume Scorched	Bole Scorch[5]	% Crown Volume Scorched	Bole Scorch[4,5]
Light	Low	≤ 10 (≥ 75)	≤ 20	≤ 10	30-50% of circumference charred to ≤ 1.5 ft. on bole.	N/A[6]	N/A
	Med	N/A	N/A	≤ 10	30-100% of circumference charred to ≤ 2 ft. on bole or ≤ 30% of circumference charred 2-5 ft. on bole.	N/A	N/A
	High	N/A	N/A	N/A	N/A	None	100% of circumference charred to ≤ 6 in. when duff layer is completely consumed.
Moderate	Low	10-20 (≥ 60)	≤ 30	≤ 20	75-100% circumference charred 3-5 ft. on bole.	N/A	N/A
	Med	20-30 (≤ 50)	< 40	20-30	50-75% of circumference charred 3-5 ft. on bole.	N/A	N/A

	High	30-40 (≤ 40)	≥ 40	20-30	30-50% of circumference charred 5-8 ft. on bole.	None	≤ 30% of bole length charred.

Table 1. Continued.

Burn Severity	**Beetle- and Fire-Mortality Risk**	**Ponderosa Pine**[1]		**Douglas-fir**[1]		**Engelmann Spruce**[2]	
		% Crown Volume Scorched (% green buds & needle bases[3])	% Bole Scorch[4]	% Crown Volume Scorched	Bole Scorch[5]	% Crown Volume Scorched	Bole Scorch[4,5]
Severe	**Low**	N/A	N/A	N/A	N/A	N/A	N/A
	Med	60-70 (≤ 20)	≥ 40	30-40	< 50% of circumference charred ≥ 8 ft. on bole.	N/A	N/A
	High	≥ 70 (≤ 10)	≥ 40	≥ 40	≥ 50% of circumference charred ≥ 8 ft. on bole.	≤ 10	≥ 30% of bole length charred.

[1]Percentage of crown volume scorched based on data from Wyant et al. (1986), for 10-inch average diameter (dbh) trees.
[2]Crown volume and bole length scorch data produced, with modification, from mortality nomograms (see Reinhardt and Ryan, 1988) for an average diameter tree of 14 in. (dbh) with 70% crown ratio, assuming a "LOW" tree mortality rate of 20%, a "MODERATE" mortality rate of 40%, and a "HIGH" mortality rate of 50% or more.
[3]Percent of remaining crown with live (green) buds and needles with green bases. Radiant or convective heating can injure foliage without causing scorching. In this case, heat-injured foliage turns a dull green color but may still contain some live buds and needles with green bases.
[4]Percent of total tree height scorched.
[5]Percentage bole scorch represents surface area charred circumferentially around the bole.
[6]Not applicable.

Table 2. Fire mortality risk considerations for selected conifer species based on first- and second-order fire effects visual indicators.

Burn Severity	Fire-Mortality Risk	Western Larch[1]		Lodgepole Pine[2]		Grand Fir/White Fir[3]		Subalpine Fir[1]	
		% Crown Volume Scorched	Bole Scorch	% Crown Volume Scorched	Bole Scorch	% Crown Volume Scorched	Bole Scorch[4,5]	% Crown Volume Scorched	Bole Scorch
Light	**Low**	N/A[6]	N/A	None	$\leq$ 30% of basal circumference charred at 1.5 ft. above ground	None	$\leq$ 30% of basal circumference charred at $\leq$ 1.5 ft. above ground	None	No visible bole scorch, but cambium may be killed by radiant or convective heat from nearby burning fuels (check with hand axe). Roots also may be killed by long-duration surface fires (e.g., smoldering duff).
	Med	N/A	N/A	$\leq$ 30	$\leq$ 30% of basal circumference charred at 1.5 ft. above ground	N/A	N/A	$\leq$ 20	No visible bole scorch, but cambium may be killed by radiant or convective heat from nearby burning fuels (check with hand axe). Roots also may be killed by long-duration surface fires (e.g., smoldering duff).

	High	N/A	N/A	N/A	N/A	$\leq$ 10	$\leq$ 30% of bole length charred. or 100% of circumference charred to $\leq$ 6 in., especially if duff layer completely consumed resulting in root mortality.	$\leq$ 20	100% of bole circumference charred to $\leq$ 6-inches on bole.

Table 2. Continued.

Burn Severity	**Fire-Mortality Risk**	**Western Larch[1]**		**Lodgepole Pine[2]**		**Grand Fir/White Fir[3]**		**Subalpine Fir[1]**	
		% Crown Volume Scorched	Bole Scorch	% Crown Volume Scorched	Bole Scorch	% Crown Volume Scorched	Bole Scorch[4,5]	% Crown Volume Scorched	Bole Scorch
Moderate	**Low**	$\leq$ 65	Bole circumference charred to $\geq$ 60% of bole length.	N/A	N/A	N/A	N/A	N/A	N/A
	Med	N/A	N/A	$\leq$ 40	30-40% of bole circumference charred at 1.5 ft. above ground line.	N/A	N/A	$\leq$ 30	50-75% of bole circumference charred to 6-12 inches on bole.
	High	N/A	N/A	$\leq$ 50	40-60% of bole circumference charred at 1.5 ft. above ground line.	10-20	30-40	$\leq$ 40	75-100% of bole circumference charred to 6-12 inches on bole.
Severe	**Low**	65-80	100% of bole circumference charred to $\geq$ 70% of bole length.	N/A	N/A	N/A	N/A	N/A	N/A

	Med	$\geq$ 90	100% of bole circumference charred 70- 80% of bole length.	50-70	$\geq$ 60% of bole circumference charred at 1.5 ft. above ground line.	N/A	N/A	N/A	N/A
	High	100	100% of bole circumference charred $\geq$ 80% of bole length.	70-100	100% of bole circumference charred at 1.5 ft. above ground line.	$\geq$ 20	$\geq$ 40	$\leq$ 50	100% of bole circumference charred to > 1 ft. on bole

[1]Crown scorch data modified from simulation modeling by Peterson (1983), based on 15.7-inch diameter (dbh) trees.

[2]Crown and bole scorch data adapted from Peterson and Arbaugh (1986), based on average tree diameter (dbh) of 10 inches.

[3]Crown volume and bole length scorch data produced, with modification, from mortality nomograms (see Reinhardt and Ryan, 1988) for an average diameter tree of 8 in. (dbh) with 70% crown ratio, assuming a "LOW" tree mortality rate of 20%, a "MODERATE" mortality rate of 40%, and a "HIGH" mortality rate of 50% or more. Large diameter trees, having thicker bark, may survive ground fires that typically kill smaller diameter trees with thinner bark.

[4]Percent of total tree height scorched.

[5]Percentage bole scorch represents surface area charred circumferentially around the bole.

[6]Not applicable.

Discussion of Burn Severity Guidelines

The guidelines, while considered to be in working draft form, should continue to undergo scrutiny and modification as they are being used by district personnel and modified by additional research and observations. These guidelines were developed through piecemeal efforts, drawing upon both scientific information, where such exists, and professional experience. It must be understood that the guidelines provided are at the single tree scale, but the actual prescribed burning is done at the landscape scale. Therefore, judgement by experienced practitioners of prescribed fire is needed to transition between these different scales and apply them at a landscape scale to achieve desired fire-effects results, while considering the objectives of the burn.

Comments from district foresters and sale administrators who applied the first version of the guidelines to salvage sales were favorable. Most indicated that "leave" tree survival was upwards of 95 percent the first year after fire salvage. Most of the mortality of leave trees occurred where the trees had been substantially weakened by drought and diseases prior to the fire. For example, fire-injured western larches that had been severely damaged by larch dwarf mistletoe (*Arceuthobium laricis*) prior to the fire were among those individuals that eventually succumbed to their fire-injuries. In some cases, foresters observed that these early guidelines may have underestimated survival of Douglas-fir, larch, and certain grand fir and white fir the year after the fire. Apparently situations occur where trees could withstand more bole and crown scorch than indicated by the early Burn Severity Guidelines. Efforts have been made to correct these problems in the present version. Only with long-term (5 years or more) monitoring of post-fire tree survival can some of these issues surrounding success in applying these guidelines be reasonably resolved.

Undoubtedly, other changes will occur in future versions as these guidelines are put to use in the field. We may never be able to cover all the conditions and every case under which fire-injured trees become susceptible to insects, but an adaptive management process should help improve results of using the guidelines through mid-course corrections and incremental adjustments, as improvements are identified. To this end, the authors solicit comments and suggestions for improvements from those who apply these guidelines to landscape underburns.

The current guidelines are drawn from information from diverse sources. Research studies that support some of these guidelines were conducted by different scientists, at different locations, and under different conditions; hence, the guidelines have been developed around different average tree diameters for the various species. Consequently, the degree of injuries that lead to tree mortality will vary slightly for tree diameters larger or smaller than those used in developing these guidelines. Some degree of personal interpretation based on professional judgement will be necessary for assessing all cases. As much as possible, tree diameters were selected to represent the approximate lower limit that a particular tree species typically becomes susceptible to their insect predator in the absence of fire injuries.

Special Cases:

Special mention should be made of a few cases to reiterate and emphasize particular conditions of tree injury after a burn. These are sometimes misinterpreted due to subtleties of the nature of heat injury to foliage, and bole and root cambium.

The first case occurs in ponderosa pine when healthy foliage is subjected to **convective heat damage** from hot gases rising above the fire, or when exposed to **superheated air** during certain fire behavior conditions. The "standard" lethal time-temperature for plant protoplasm resulting in tissue death is generally agreed to be 60°C for 1 minute (Agee, 1993). Heat-related injuries to conifer needles that result in fixation of living tissues through the precipitation and denaturing of proteins and enzymes are common during wildfires or prescribed fires. During the exposure to heat from hot air and combustion gases needles are quickly desiccated, if not consumed in combustion, and low-molecular weight terpenoid and other compounds are rapidly altered and volatilized during thermochemical processes. Numerous other changes also occur; hence excessive heating causes a multiplicity of changes to the physiology and biochemistry of healthy foliage. As previously mentioned, these processes cause foliage to appear dull green in color; but, in many cases the buds have not been killed (see fig. 4.). It is especially important to pay particular attention to the condition of buds on ponderosa pine after a fire. Severe heat injury to ponderosa pine foliage does not always equate to tree death. Other factors also need to be considered in assessing the survivability of this species. These are covered to a large extent in the guidelines.

The second case we call "**green-death**," or the apparent healthy appearance of grand fir or white fir after fires, particularly ground fires. A green crown on these trees does not necessarily indicate they have survived exposure to the fire. Unless the tree has very thick bark, it is not likely to survive more than 2 or 3 seasons after the burn. Active xylem continues to keep the crown hydrated, but severe root damage and girdling at the root collar from long residence heating of these structures by slowly smoldering duff inhibits translocation of elaborated foodstuffs needed to repair damaged root tissues and cambium. The shallow root systems and sensitive cambium beneath thin bark of these trees do not withstand heat from fires very well. Many of these trees die the year after the burn. Others may survive a year longer depending on various factors.

Most fire studies addressing post-fire tree survival place greater importance on crown damage than bole damage. In most situations it is certainly easier to quantify crown scorch and link this damage to tree survival than to do the same with bole scorch because so much of the injury that is critical to the survival of the tree is hidden from direct view in the latter. The most accurate way to determine dead cambium, of course, is to remove portions of the bark to observe the cambium directly. The only non-destructive method we know of to evaluate cambium mortality is to measure electrical conductivity in the cambial region with a moisture meter (Hare 1960); but this may not be practical. Fahnestock and Hare (1964) observed that pitch flow on the bark could reliably be used to indicate dead cambium beneath on longleaf pines in southern Mississippi. We have observed considerable pitch production on the bark of

some scorched conifers in the Blue Mountains, especially Engelmann spruce, but have not attempted to correlate this with dead cambium. The streaming of clear pitch often originates from the locations where branches joined the bole, when the branches become broken off the bole of some conifer species like Engelmann spruce. The bark of Engelmann spruce also seems to exude pitch when it has been injured by heat. So pitch production and streaming on the bark surfaces of fire-injured trees, as an indicator of dead cambium beneath the bark, should be used with caution.

In developing the guidelines reported here, we have attempted to include a classification for bole scorch, even though it is highly variable as a surrogate for cambium damage, because we believe it is still a necessary criterion that can be used to help separate different levels of risk to insects. In addition, Ryan and Reinhardt (1988) suggest that interactions between fire-caused injuries are likely involved in post-fire mortality of conifers. Furniss (1965) indicated that crown injury and cambium injury tend to be correlated, though this may vary with type of fire. Where empirical data on bole scorch-related tree mortality were available in scientific literature, these data were used, or adapted, for the purpose of developing the present guidelines. Where reasonable data were not available or were limited, professional judgement based on field observations was used to establish bole scorch criteria in the guidelines.

Given that variable results of tree survivability can be expected from the guidelines, several generalities can be made about survivability of different species based on the guidelines. Experience has found that using the guidelines, one can predict that previously healthy ponderosa pines and western larches experiencing only a **light** to **moderate** burn severity, should survive the fire; nonetheless, mortality risk within these burn severity categories may still vary. Ponderosa pines that were severely weakened or already fading due to drought stress, root disease, and/or bark beetle attacks will not survive even a **light** burn. Similarly, in the severely dwarf mistletoe-infected larch example above, these trees will not survive **moderately** severe fire injuries, and may not survive **light** fire injury beyond the first season or two.

Light and **Moderate** burn severity will cause some mortality in Douglas-fir. Generally, Douglas-fir beetles can be expected to play some role in this mortality based on past experience (fig. 6.), particularly as the **severely** fire-injured host trees are depleted by beetles. If Douglas-fir beetle populations are locally high, or increase rapidly on the burn, not only will **moderately**-injured trees be increasingly attacked by bark beetles over the next couple of seasons after the fire, but **lightly**-injured, and some **uninjured** host trees will be attacked and killed by beetles, as well (fig. 6.). Douglas-firs which have less than 20-percent crown scorch have the best chances for survival. Furniss (1965) suggests that trees defoliated less than 20 percent by fire have less than or equal to 50 percent chance of being attacked by Douglas-fir beetles. Crown scorch during wildfires appears to be much more important in contributing to mortality of Douglas-fir than in ponderosa pine. However, in studies conducted by Ryan et al. (1988), cambium injury from low-intensity prescribed fires in Douglas-fir turned out to be a stronger predictor of tree mortality than crown scorch.

Light burn severity will frequently result in mortality in more fire-sensitive white or grand fir, subalpine fir, Engelmann spruce, and lodgepole pine, than in the early seral species. This is due largely to the thinner bark, shallow root systems, high live crown-to-bole ratio, and sometimes persistence of dead lower limbs on these species making them more subject to lethal injuries from fire. Probably most trees of these species experiencing **moderate** injury from fire, and virtually all trees of these species experiencing **severe** fire injury, will not survive the fire. As before, variable mortality risk levels exist within each burn severity category.

Measures to Minimize Fire Injuries From Prescribed Burns

1. Determine acceptable mortality "risk" levels for desirable trees.

   Tables 1 and 2 can be used to determine acceptable levels of risk from fire and insects after an underburn. This should be the first step in developing the burn prescription. After resource objectives have been identified, and agreement reached on what constitutes "acceptable" damage given the level of mortality risk associated with the damage, fire personnel can then determine the appropriate burn prescription parameters necessary to meet both the resource objectives and acceptable damage level objectives.

2. Minimize crown injury.

   Cause: Convection heating of foliage by hot gases rising above the fire (Ryan, 1988).

   Remedy: Flame length is the visual fire characteristic most closely associated with crown scorch, and is primarily dependent on the rate of ignition and combustion of fine surface fuels (Ryan, 1988). Crown scorch can be mitigated by:

   (a) Restricting burning from around specific individual or groups of desirable leave trees, if it cannot be reasonably done without exceeding acceptable levels of crown damage.

   (b) Carefully manage ignition pattern of fuels where the unit average 1-hour and 10-hour time-lag fuel loadings and their moisture contents are such that flame lengths would result in unacceptable crown scorching of desirable tree species (see Tables 1 and 2 to determine acceptable levels of resource risk; see Ryan, 1988, for lists of references on techniques for estimating crown kill, fire line intensity, scorch height, flame length, and others).

3. Minimize root injury.

Cause: Conduction of heat downward from the fire causes root injury (Ryan, 1988). Fires that burn with long residence time over root systems create heat loads that can seriously damage roots.

Remedy: Establish desired amounts of duff consumption during the burn, especially in regard to minimizing root injuries in desirable leave tree species. Ryan (1988) indicates that duff moisture contents below 35% generally results in nearly complete duff reduction, and that consumption of thin duff is inversely related to increasing moisture contents above this amount. Moreover, he states that deep duff may burn at moisture contents as high as 90% based on studies by Harrington and Sackett (1990), but that duff consumption is minimal at moisture contents above 120%. Root injury can be mitigated based on information offered by Ryan (1988):

(a) "When duff is wet (ca. 120%) expect minimal root injury."

(b) "If duff is deeper than 4 in (ca 10 cm) and drier than about 35%, basal girdling may be a problem for all but the thickest barked trees."

(c) "In deep-rooted trees expect little additional mortality due to root injury unless duff consumption is also expected to be greater than 4 in (10 cm)."

(d) "Expect shallow-rooted species to experience root injury in any prescription that calls for more than 1.2 in (ca 3 cm) of duff consumption."

4. Minimize stem injury.

Cause: The dead outer bark insulates the active life processes of the inner phloem and the living cambium of the stem from fire injury. These stem tissues are injured when heat produced by the fire is conducted through the dead outer bark and penetrates to the underlying tissues (Ryan, 1988). The residence time of active flaming (Rothermal and Deeming, 1980; cited in Ryan, 1988), and to a lesser degree the residual burnout (Ryan, 1988) are responsible for stem injury in trees of a given bark thickness.

Remedy: Minimizing consumption of the larger woody fuels near the tree is necessary to minimize the duration of high-temperature exposure of the

stem, and reduce stem damage (Ryan, 1988). In addition, the thickness of the bark on desired leave trees is a critical factor in the ability of cambium to resist injury. For example, Ryan (1988) notes the following:

> "Trees with less than 0.2 cm of bark will likely die in any fire vigorous enough to encircle them. Trees with 0.2-0.5 cm of bark can resist cambium injury in short duration surface fires. In most operational burns in natural fuels the minimum bark thickness necessary for consistent cambium survival is around 1.0 cm. Prevention of excessive cambium injury during slash burning requires at least 2.0 cm of bark. Our data indicate that less than 5% of the cambium is killed in operational slash burns when bark is thicker than 4 cm. Injury beneath thick bark, except at the root crown, is exclusively associated with burnout of logs, so it is not advisable to burn with heavy fuels on more than one side of a tree unless they are too wet to burn effectively. Concentrations of logs may burn independently of smaller fuels and at moisture contents above 20%. Consumption of individual logs, however, should be minimal above 20%."

It is clear that there is no simple guideline to avoid or minimize damage to stems of desired trees because of the complexity and scale of factors involved. Our best advice is offered in general terms and as considerations that can be used to understand risk gradients. They are based on lethal exposure times for cambium of specified diameter trees of different species and bark thicknesses (see Ryan, 1982, 1988; Ryan and Reinhardt, 1988). Exposure times for other diameters, or for other species can be computed using the references listed:

(a) Avoid burning in fuel conditions within 1 meter from around any 8- to 12-inch ponderosa pine or Douglas-fir tree, that would result in exposure of the tree bole to longer than 2.0 minutes of fuel combustion duration to burnout. For 8- to 12-inch western larch, the maximum fuel combustion-to burnout time is 1.5 minutes. If stated fuel conditions cannot be met, pull fuels away from tree bole, leaving fuels widely scattered (not piled) outside the 1 meter radius of the bole, or burn only during higher fuel moisture conditions.

(b) Avoid burning in fuel conditions within 3.3 ft (ca. 1 meter) from around any 21-inch ponderosa pine or Douglas-fir tree, that would result in exposure of the tree bole to longer than 4.1 minutes of fuel combustion duration to burnout. For 21-inch western larch, the maximum fuel combustion-to burnout time is 3.6 minutes. If stated fuel conditions cannot be met, pull fuels away from tree bole, leaving fuels widely scattered (not piled) outside the 3.3 ft (ca. 1 meter) radius of the bole, or burn only

during higher fuel moisture conditions.

(c) Avoid burning in fuel conditions within 3.3 ft (ca. 1 meter) from around any 30-inch ponderosa pine or Douglas-fir tree, that would result in exposure of the tree bole to longer than 5.8 minutes of fuel combustion duration to burnout. For 30-inch western larch, the maximum fuel combustion-to burnout time is 5.3 minutes. If stated fuel conditions cannot be met, pull fuels away from tree bole, leaving fuels widely scattered (not piled) outside the 3.3 ft (ca. 1 meter) radius of the bole, or burn only during higher fuel moisture conditions.

5. Modify characteristics of available fuels to optimize conditions for desired fire behavior.

Environmental conditions can be advantageously used to help modify fire behavior characteristics. Diurnal changes in fine fuel moisture, air temperature, and wind speed will modify crown scorch (Ryan, 1988). Fuel moisture conditions at night, and cooler nighttime air temperatures help slow combustion and allow recovery of fuel moisture lost during the day. However, duff consumption and duff burnout may not be substantially affected by diurnal changes in moisture or air temperature, respectively (Ryan, 1988), but light wind may somewhat improve duff burnout. To minimize burning of duff, moisture from rainfall is necessary to rehydrate dry duff. Amounts of rainfall usually approaching one-third the depth of the duff is needed to rehydrate dry duff (Ryan, 1988). Some of the heat produced in woody combustion is used to evaporate water when woody fuels and soils are moist. In addition, moist earth is a good absorber of both long and short wavelengths of radiant energy (Reifsnyder and Lull, 1965). Since fires radiate in the near infrared wavelengths (short wavelengths), a portion of the radiation may be absorbed by moisture-bearing fuels and the soil, thereby helping to reduce heat injury to desirable live trees.

(a) Burn at night or after appropriate amounts of rainfall to take advantage of the effect of modified fuel moisture and air temperatures on fire behavior characteristics. Except for very high-value trees, pre-ignition removal or direct wetting of duff around tree bases may be impractical (Ryan, 1988). However, there may be special cases when duff removal or wetting may be justified, so these measures should not be entirely discounted.

(b) To further reduce stem injuries, burn when 10-, 100-, and 1000-hour fuels are sparse in the area from about the tree base to 6.6 ft (ca. 2 meters) out from the desirable tree, or when they are too wet to burn (Ryan, 1988), unless these conditions seriously limit burning

opportunities and conflict with burn objectives. Ryan (1988) suggests other alternatives to help reduce stem injuries in addition to removing woody fuels from around the tree, including treating fuels with fire retardant chemicals, foam, or water. Since results of some of these treatments are quite variable, and the procedures may not be practical, they are only listed as possible alternatives and not necessarily as recommendations.

The removal of 100-hour time-lag fuels from around desirable trees are especially important because these are the primary source of injury in moderately thick-barked trees (Ryan, 1988). Removal of these fuels from within 3.3 ft (ca. 1.0 meter) of trees is recommended by Ryan (1988) if they occur on more than one side unless bark is thicker than ¾-1¼ in (ca 2-3 cm). Also, the 1000-hour time-lag fuels should be removed if they occur on more than one side and are dry enough to burn. In every case, removal should be a minimum distance of 3.3 ft (ca. 1.0 meter); however removal of fuels for a greater distance from trees may be necessary depending on the amount of fuel and the thickness of the bark of trees (Ryan, 1988). Kilgore and Curtis (1987) suggest removing fuels from at least 6 feet around the bole of a tree during underburning of activity fuels in pine-larch-fir types when total fuel loading exceeds 30 tons/acre and when less-than-3-inch diameter fuels exceed 10 tons/acre unless all trees are 20 inches d.b.h. or larger and there are adequate holes in the canopy for heat and smoke to escape. Some Districts report removing all fuels within 25 feet of superior seed trees (Kilgore and Curtis, 1987).

Always remove the fuel to the side, **never** up hill or down hill or on the windward side of the tree (Ryan, 1988; our emphasis added). Ryan (1982) gives additional fuel removal guidance.

6. Modify ignition patterns to manage the amount of fuel that is burning at any one time.

(a) Ignite only one strip at a time to reduce intensities of strip-head fires (Ryan, 1988). In addition, Ryan recommends making the width of the burn strip less than the maximum flame zone depth. Generally, burn strips of less than 13.1 ft (ca. 4.0 meters) will reduce flame lengths enough to reduce crown scorch (Ryan, 1988).

(b) Avoid lighting several strips close together in time and space to prevent increasing surface fire intensity, and ultimately crown scorch and bole injuries (Ryan, 1988).

(c) Limit backing fires to fine fuel and duff conditions that will limit fire duration to minimize exposure of root systems and bole to heat. Minimize use of backing fire on steep slopes to reduce bole injuries, especially high on the bole, from burnout of fuels at the base and from below the tree, and also heat on the uphill side of the bole as the backing fire approaches the tree (Ryan, 1988).

(d) Make limited use of strip-head and backing fires in spruce-fir stands to avoid injuries to bole cambium and sensitive shallow root systems. Alexander (1987) warns:

> "Thin bark, persistence of dead lower limbs, and shallow root systems make spruce and fir susceptible to destruction or severe injury by fire. Moreover, fire damage to the roots and boles predisposes spruce and fir to windthrow and windbreak."

Jackpot burning of activity fuels and natural fuels may better control fire behavior in these plant associations and reduce injuries to trees when piles are kept away from these trees. If strip-head and backing fires must be used, it is advisable to remove fuels several meters away from potential leave trees to avoid injury and subsequent windthrow or windbreakage.

7. Reduce heavy fuels during harvest operations or use a 2-tiered fuels treatment approach when predicted fuel loadings are excessive and could result in flame lengths that would cause excessive injury to crowns.

Activity and natural fuel loadings that exceed 35 tons/acre will cause excessive crown scorch if special precautions are not taken to reduce flame lengths and mitigate first-order fire effects. Reduction of fuels to less-than-3-inch diameter can be accomplished by several methods described by Kilgore and Curtis (1987). For natural fuels, they suggest using a 2-tiered strategy of treating fuels by burning.

(a) "In natural fuels, schedule two understory burns, or a jackpot burn of heavier fuels followed by broadcast understory burning of lighter fuels."

(b) "In activity fuels, your slash plan should specify tree length yarding or yarding tops of certain species to reduce less-than-3-inch fuels to an acceptable loading. Limbing should be done at the landing rather than in the woods."

8. Utilize the mosaic burn patterns of landscape underburning to emulate the diversity of natural, historic fire patterns and processes across the landscape.

Certain fuel conditions may exist around some desirable trees within a burn unit

that make it neither practical nor feasible to remove or pre-treat fuels to protect trees from excessive injury prior to burning. The resource manager may elect to "back away" from burning portions of an area because of the high risk of tree mortality, as well as to use fire to create landscape diversity and emulate mosaic burn patterns of historical fire events. It is not absolutely necessary to blacken every square foot of the landscape being treated with fire, even though we may be capable of doing so.

On the other hand, it is not possible to keep every living tree alive after the burn. Our concern is to avoid creating situations that cause bark beetle populations to build up and put the remaining trees at high risk. Bark beetles are extremely aggressive and opportunistic organisms. Their impact on a stand after a burn should not be underestimated.

Summary

Just as it is important to minimize injury and weakening of trees during harvest activities to avoid future insect or disease problems, it is equally important to minimize the level of injury to trees after a prescribed fire for the same reason. We have described conditions of fire-injury in the foregoing that may result in the attraction of insect populations of significant concern to stand health and tree survival after a fire, regardless of fire origin. Under favorable conditions, populations of tree-killing bark beetles can, and do, build up very quickly in the presence of suitable habitat (i.e., fire-weakened hosts). An increased awareness of the fire-injury conditions that favor these buildups can help establish thresholds of acceptable damage from a prescribed fire.

The increasing areas of eastside forests that annually burn in lightning-caused wildfires, and the increased use of landscape underburning to achieve ecosystem management objectives dictates the need for better information on insect-fire interactions and fire effects on (1) tree and vegetation survival, recovery, and growth; (2) forest pathogens; (3) soil and hydrologic processes; and (4) wildlife populations and habitat. The burn-severity guidelines given here address, at least in part, some of these issues. Specifically, we have presented guidelines that will: (1) assist resource managers in identifying and assessing risk of tree mortality from fire and/or insects after prescribed burns or natural wildfires; (2) assist planning teams achieve resource management objectives for prescribed fires or landscape underburns while establishing acceptable levels of post-fire mortality risk; and (3) assist fire planners in developing or refining burn prescriptions that avoid unacceptable losses of trees from heat injuries and insects after treatment.

To provide practical solutions and mitigation for tree survival when carrying out burn prescriptions under varying conditions, we offer the fire planner a set of guidelines. The guidelines can be implemented in part or in total, or modified within reason, to meet the needs of individual prescribed fire situations. The guidelines are not intended as direction, but only as suggestions to help achieve post-treatment resource and fire objectives, and avoid untoward consequences from fire or insects during, and after, landscape underburning.

As a final recommendation, we place heavy emphasis on the need to conduct post-treatment monitoring of fire effects. Follow-up evaluations are essential to measure results against expectations, and to identify unanticipated problems. These activities are inherent to adaptive management.

There is no such thing as a perfect world; especially in the practice of forestry and forest resource management. Forests exist over a continuum of time and experience many different forms and degrees of disturbances during the lifespans of the trees that occur there. Measured on a forest's time-scale, modern human influence on forest ecosystems seems rather inconsequential; yet human influences on the forests in just the past 150 years are responsible

for considerable changes from the forests of earlier times. Vegetation has undergone considerable successional change in many areas as a result of selective harvest activities and fire exclusion and suppression practices that have occurred mostly during the last 70 or 80 years. However, there are no broad-scale processes or pathways by which we can cause large changes in significant portions of the landscape at any one time, or at any given moment. In short, there are no "quick fixes" to forest health. There are only minute windows of management opportunities momentarily transfixed in time and space by their unique set of results and consequences. It is upon these management opportunities that we can expand our knowledge and understanding of how the complexities and intricacies of the systems comprising the forest works.

As we capitalize on opportunities along the path of ecosystem management, we will make a number of mistakes. We will also adapt and adjust as appropriate to improve the results, reduce the frequency of undesirable consequences, and hopefully discover new windows of opportunity for ecosystem management that we can exploit in the future. So it is with landscape underburning. It is not critical that we conduct the "perfect" underburn, but rather that we learn from what we've done, each time it's done, and seek new ways to improve the "art" of plying our craft. We hope the information contained in this report provides a useful resource to those involved in planning and conducting landscape underburns, as well as accomplishing the other purposes that were described in the beginning.

Acknowledgement

We thank Drs. Richard Mason, Torolf Torgersen, and Andy Youngblood, Pacific Northwest Research Station, and Suzanne Rainville and the Fire and Fuels Specialists of Wallowa-Whitman National Forest, for their helpful comments and suggestions on an earlier draft of this document.

Literature Cited

Agee, J. K. 1973. Prescribed fire effects on physical and hydrologic properties of mixed-conifer forest floor and soil. University of California Water Resources Center, Contribution No. 143.

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Island Press. Washington, D.C. 439 p.

Agee, J. K. 1994. Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades. Gen. Tech. Rep. PNW-GTR-320. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 52 p. (Everett, Richard L., assessment team leader; Eastside forest ecosystem health assessment; Hessburg, Paul F., science team leader and tech. ed., Volume III: assessment.)

Alexander, R. R. 1987. Ecology, silviculture, and management of the Engelmann spruce-subalpine fir type in the central and southern Rocky Mountains. Agr. Handb. No. 659. Washington, D. C.: U. S. Department of Agriculture, Forest Service. 144 p.

Bartos, D. L.; and G. D. Amman. 1989. Microclimate: an alternative to tree vigor as a basis for mountain pine beetle infestations. Res. Pap. INT-400. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Research Station. 10 p.

Bartos, D. L.; and G. D. Booth. 1994. Effects of thinning on temperature dynamics and mountain pine beetle activity in a lodgepole pine stand. Res. Pap. INT-RP-479. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Research Station. 9 p.

Bedard, W. D. 1950. The Douglas-fir beetle. Circ. No. 817. Washington, D. C.: U. S. Department of Agriculture. 10 p.

Berryman, A. A. 1986. Forest insects: principles and practice of population management. Plenum Press. New York. 279 p.

Camp, A. E.; P. F. Hessburg; R. L. Everett. 1996. Dynamically incorporating late-successional forest in sustainable landscapes. *In* C. C. Hardy; and S. F. Arno (eds.), The use of fire in forest restoration. Gen. Tech. Rep. INT-GTR-341. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Research Station. p. 20-23.

Dolph, R. E., Jr. 1980. Budworm activity in Oregon and Washington, 1947-1979. Rep. R6-FIDM-033. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Region, State and Private Forestry, Forest Insect and Disease Management. 54 p.

Dolph, R. E., Jr. 1982. Relationship of lodgepole pine and ponderosa pine stand density of susceptibility to beetle infestations. *In*: 1982 Western Forestry Conference: proceedings of a conference; Western Forestry and Conservation Association. Portland, OR. p. 22.

Eaton, C. B. 1941. Influence of the mountain pine beetle on the composition of mixed pole stands of ponderosa pine and white fir. Journal of Forestry 39: 710-713.

Fahnstock, G. R.; and R. C. Hare. 1965. Heating of tree trunks in surface fires. Journal of Forestry 62: 799-805.

Fischer, W. C. 1980. Prescribed fire and bark beetle attack in ponderosa pine forests. Fire Management Notes 41 (Spring): 10-12.

Furniss, M. M. 1965. Susceptibility of fire-injured Douglas-firs to bark beetle attack in southern Idaho. Journal of Forestry 63: 8-11.

Furniss, R. L.; and V. M. Carolin. 1977. Western forest insects. Misc. Publ. No. 1339. Washington, D. C.: U. S. Department of Agriculture, Forest Service. 654 p.

Gara, R. I.; W. R. Littke; J. K. Agee; D. R. Geiszler; J. D. Stuart; and C. H. Driver. 1985. Influence of fires, fungi, and mountain pine beetles on development of a lodgepole pine forest in south-central Oregon. *In* Baumgartner, D. M., et al. (eds.), Lodgepole pine: The species and its management. Washington State University, Pullman. p. 153-162.

Gast, W., Jr.; D. Scott; C. Schmitt; D. Clemens; S. Howes; C. Johnson; R. Mason; F. Mohr; and C. Clapp, Jr. 1991. Blue Mountains Forest Health Report: New perspectives in forest health. [unnumbered report]: USDA, Forest Service, Pacific Northwest Region, Malheur, Umatilla, and Wallowa-Whitman National Forests. [Unconventional pagination].

Geiszler, D. R.; R. I. Gara; C. H. Driver; V. F. Gallucci; and R. E. Martin. 1980. Fire, fungi, and beetle influences on a lodgepole pine ecosystem of south-central Oregon. Oecologia 46: 239-243.

Geiszler, D. R.; R. I. Gara; and W. R. Littke. 1984. Bark beetle infestations of lodgepole pine following a fire in south-central Oregon. Z. ang. Ent. 98: 389-394.

Grier, C. C. 1989. Effects of prescribed springtime underburning on production and nutrient status of a young ponderosa pine stand. *In* Multiresource management of ponderosa pine forests. U. S. Department of Agriculture, Forest Service, Gen. Tech. Rep. RM-185. p. 71-76.

Guralnik, D. B.; and J. H. Friend (gen. eds.). 1966. Webster's new world dictionary, college edition. Cleveland, OH: The World Publishing Company. 1724 p.

Hall, F. C. 1976. Fire and vegetation in the Blue Mountains--implications for land managers. Tall Timbers Fire Ecology Conference Proceedings. 15: 155-170.

Hare, R. C. 1960. Detecting dead cambium with a moisture meter. Journal of Forestry 58: 815-817.

Harrington, M. G.; and S. S. Sackett. 1990. Fire as a tool for reducing fuels, thinning stands, and facilitating natural regeneration in southwestern ponderosa pine. *In* Effects of fire in management of southwestern natural resources: conference proceedings, Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station Gen. Tech. Rep. RM-191. p. 122-133.

Hessburg, P. F.; R. G. Mitchell,; and G. M. Filip. 1994. Historical and current roles of insects and pathogens in eastern Oregon and Washington forested landscapes. Gen. Tech. Rep. PNW-GTR-327. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 72 p. (Everett, Richard L., assessment team leader; Eastside forest ecosystem health assessment; Hessburg, Paul F., science team leader and tech. ed., Volume III: assessment.)

Johnson, C. G.; R. R. Clausnitzer; P. J. Mehringer; and C. D. Oliver. 1993. Biotic and abiotic processes of eastside ecosystems: the effects of management on plant and community ecology, and on stand and landscape vegetation dynamics. In: Hessburg, P. F., science team leader and tech. ed., Eastside forest Ecosystem health assessment, Volume III: assessment. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. p. 35-99.

Kaufmann, M. R.; R. T. Graham; D. A. Boyce, Jr.; W. H. Moir; L. Perry; R. T. Reynolds; R. L. Bassett; P. Mehlhop; C. B. Edminster; W. M. Block; and P. S. Corn. 1994. An ecological basis for ecosystem management. Gen. Tech. Rep. RM-246. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and

Range Experiment Station. 22 p.

Keen, F. P. 1952. Insect enemies of western forests. Misc. Publ. No. 273. Washington, D. C.: U.
S. Department of Agriculture. 280 p.

Kilgore, B. M.; and G. A. Curtis. 1987. Guide to understory burning in ponderosa pine-larch-fir
forests in the Intermountain West. Gen. Tech. Rep. INT-233. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Research Station. 39 p.

Kramer, P. J.; and T. T. Kozlowski. 1979. Physiology of woody plants. Academic Press, Inc. Orlando, FL. 811 p.

Lehmkuhl, J. F.; P. F. Hessburg; R. L. Everett; M. H Huff; and R. D. Ottmar. 1994. Historical and current forest landscapes of eastern Oregon and Washington. Part I: vegetation pattern and insect and disease hazard. PNW-GTR-328. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 88 p. (Everett, R. L., team leader; Eastside forest ecosystem health assessment; Hessburg, P. F., science team leader and tech. ed., Volume III: assessment).

Littke, W. R.; and R. I. Gara. 1986. Decay of fire-damaged lodgepole pine in south-central Oregon. For. Ecol. and Manage. 17: 279-287.

Martin, R. E. 1963. Thermal properties of bark. U. S. For. Prod. J. 13: 419-426.

Mason, R. R. 1993. The role of pest interactions in forest health and productivity. *In* Foresters together: meeting tomorrow's challenges: proceedings, 1993 Society of American Foresters National Convention, Indianapolis, IN, November 7-10, 1993. p. 95-100.

Miller, J. M.; and F. P. Keen. 1960. Biology and control of the western pine beetle. Misc. Publ.
No. 800. Washington, D. C.: U. S. Department of Agriculture, Forest Service. 381 p.

Miller, J. M.; and J. E. Patterson. 1927. Preliminary studies on the relation of fire injury to bark
beetle attack in western yellow pine. J. Agr. Res. 34: 597-613.

Morgan, P; S. C. Bunting; A. E. Black; T. Merrill; and S. Barrett. 1996. Fire regimes in the Interior Columbia River Basin: Past and present. Contract Final Report No. RJVA-INT-94913: Coarse-scale classification and mapping of disturbance regimes in the Columbia River Basin. Missoula, MT: U. S. Department of Agriculture, Forest

Service, Intermountain Research Station, Intermountain Fire Sciences Laboratory.

Mutch, Robert W.; S. F. Arno; J. K. Brown; C. E. Carlson; R. D. Ottmar; J. L. Peterson. 1993. Forest health in the Blue Mountains: a management strategy for fire-adapted ecosystems. Gen. Tech. Rep. PNW-GTR-310. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 14 p. (Quigley, T. M., ed.; Forest health in the Blue Mountains: science perspectives).

O'Hara, K. L.; P. A. Latham; P. Hessburg; and B. G. Smith. 1996. A structural classification for inland northwest forest vegatation. Western Journal of Applied Forestry 11: 97-102.

Oliver, C. D.; L. L. Irwin; and W. H. Knapp. 1994. Eastside forest management practices: historical overview, extent of their application, and their effects on sustainability of ecosystems. Gen. Tech. Rep. PNW-GTR-324. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 73 p. (Everett, Richard L., assessment team leader; Eastside forest ecosystem health assessment; Hessburg, Paul F., science team leader and tech. ed., Volume III: assessment.)

Parsons, D. J.; and S. H. DeBenedetti. 1979. Impact of fire suppression on a mixed-conifer forest. For. Ecol. Manage. 2: 21-33.

Peterson, D. L. 1983. Estimating timber damage with a simulation model. *In* The 7th conference on fire and forest meteorology: conference proceedings, Fort Collins, April 25-28, 1983. American Meteorological Society, Boston, MA, p. 159-162.

Peterson, D. L. 1984. Predicting fire-induced mortality in Northern Rocky Mountain conifers. *In* 1983 convention of the Society of American Foresters: convention proceedings, Bethesda, MD, p. 276-280.

Peterson, D. L.; and M. J. Arbaugh. 1986. Postfire survival in Douglas-fir and lodgepole pine: Comparing the effects of crown and bole damage. Can. J. For. Res. 16: 1175-1179.

Peterson, D. L.; and K. C. Ryan. 1986. Modeling postfire conifer mortality for long-range planning. Environ. Manage. 10: 797-808.

Reifsnyder, W. E.; L. P. Herrington; and K. W. Spalt. 1967. Thermophysical properties of bark of shortleaf, longleaf, and red pine. Yale University School of Forestry Bull. No. 70.

Reifsnyder, W. E.; and H. W. Lull. 1965. Radiant energy in relation to forests. Tech. Bull.

No.
1344. Washington, D. C.: U. S. Department of Agriculture, Forest Service. 111 p.

Reinhardt, E. 1993. "FOFEM" a model for predicting fire effects. *In* Resource Management: the
fire element: Managing California's fire ecosystem for the future: Proceedings of the 1993 fuels symposium; 1993 February 2-5; Sacramento, CA. Davis, CA: University of California, University Extension. p. 48.

Reinhardt, E. D.; and K. C. Ryan. 1988. How to estimate tree mortality resulting from underburning. Fire Management Notes 49(4): 30-36.

Rothermel, R. C.; and J. E. Deeming. 1980. Measuring and interpreting fire behavior for correlation with fire effects. Gen. Tech. Rep. INT-142. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 4 p.

Rundel, P. W. 1973. The relationship between basal fire scars and crown damage in giant sequoia.
Ecology 54: 210-213.

Ryan, K. C. 1982. Evaluating potential tree mortality from prescribed burning. *In* D. M. Baumgartner (ed.), Site preparation and fuels management on steep terrain: symposium proceedings, Pullman, WA. Washington State University Coop. Ext. Serv. p. 167-169.

Ryan, K. C. 1988. Predicting prescribed fire effects on trees in the interior west. *In* First interior
west fire council annual meeting and workshop: proceedings, Kananaskis Village, Alberta, Canada, October 24-27, 1988. Forestry Canada, Northern Forestry Research Centre, Edmonton, Alberta, Canada, Information Report NOR-X-309, p. 148-162.

Ryan, K. C.; and W. H. Frandsen. 1991. Basal injury from smoldering fires in mature *Pinus ponderosa* Laws. Int. J. Wildland Fire. 1: 107-118.

Ryan, K. C.; D. L. Peterson; and E. D. Reinhardt. 1988. Modeling long-term fire-caused mortality
of Douglas-fir. Forest Science 34(1): 190-199.

Ryan, K. C.; and E. D. Reinhardt. 1988. Predicting postfire mortality of seven western conifers.
Can. J. For. Res. 18: 1291-1297.

Rust, H. J. 1933. Final report on the study of the relation of fire injury to bark beetle attack in ponderosa pine, Tubbs Hill burn. Coeur d' Alene, Idaho. (unnumbered report dated February 10, 1933.)

Sackett, S. S. 1987. Soil and cambium temperatures associated with prescribed burning in two mature ponderosa pine stands in Arizona. *In* David M. Baumgartner, et al. (eds.), Ponderosa pine: The species and its management. Washington State University, Pullman, WA. p. 281.

Sartwell, C. 1971. Thinning ponderosa pine to prevent outbreaks of mountain pine beetle. *In* David M. Baumgartner (ed.), Precommercial thinning of coastal and intermountain forests in the Pacific Northwest, Washington State University, Cooperative Extension Service, Pullman, WA. p. 41-52.

Sartwell, C.; and R. E. Dolph, Jr. 1976. Silvicultural and direct control of mountain pine beetle in second-growth ponderosa pine. Res. Note PNW-268. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 8 p.

Sartwell, C.; and R. E. Stevens. 1975. Mountain pine beetle in ponderosa pine: Prospects for silvicultural control in second-growth stands. Journal of Forestry 73: 136-140.

Schmid, J. M.; and S. A. Mata. 1992. Stand density and mountain pine beetle-caused tree mortality in ponderosa pine stands. Research Note RM-515. Ft. Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 4 p.

Schmid, J. M.; and S. A. Mata. 1996. Natural variability of specific forest insect populations and their associated effects in Colorado. Gen. Tech. Rep. RM-GTR-275. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 14 p.

Schmid, J. M.; S. A. Mata; and W. K. Olsen. 1995. Microclimate and mountain pine beetles in two ponderosa pine stands in the Black Hills. Res. Note. RM-RN-532. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 12 p.

Scott, D. W. 1996. Insect response to altered landscapes: Historic range of variation of insects.

Report No. BMZ-97-2. La Grande, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Region, Wallowa-Whitman National Forest, Blue Mountains Pest Management Zone. 11 p.

Starker, T. J. 1934. Fire resistance in the forest. J. For. 32: 462-467.

Stewart, C. A.; and S. K. Hagle. 1988. Evaluation of Douglas-fir seed tree mortality on the Powell Ranger District, Clearwater National Forest, Idaho. *In* Thirty-fifth annual western international forest disease work conference: proceedings, Nanaimo, British Columbia, Canada, August 18-21, 1987. p. 105-111.

Stipe, L. E. 1987. Outbreak chronology. *In* M. H. Brookes; R. W. Campbell; J. J. Colbert; R. G. Mitchell; and R. W. Stark, (eds.), Western spruce budworm. Tech. Bull. 1694. Washington, D. C.: U. S. Department of Agriculture, Forest Service, Canada-United States Spruce Budworms Program. Chapter 1.2, p. 2-5.

Sutherland, E. K. 1988. Prescribed burning and ponderosa pine growth: What managers should know. *In* David M. Baumgartner, et al. (eds.), Ponderosa pine: The species and its management. Washington State University, Pullman, WA. p. 280-281.

Sutherland, E. K.; W. W. Covington; and S. Andariese. 1991. A model of ponderosa pine growth response to prescribed burning. Forest Ecology and Management 44: 161-173.

Swanson, F. J.; J. A. Jones; D. O. Wallin; and J. H. Cissel. 1994. Natural variability--implications for ecosystem management. In: Jensen, M. E.; Bourgeron, P. S., tech. eds., Volume II: Ecosystem management: principles and applications. Gen. Tech. Rep. PNW-GTR-318. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. p. 80-94.

Swetnam, T. W.; B. E. Wickman; H. G. Paul; and C. H. Baisan. 1995. Historical patterns of western spruce budworm and Douglas-fir tussock moth outbreaks in the northern Blue Mountains, Oregon, since A.D. 1700. Res. Pap. PNW-RP-484. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p.

Swezy, D. M.; and J. K. Agee. 1991. Prescribed fire effects on fine root and tree mortality in old-growth ponderosa pine. Can. J. For. Res. 21: 626-634.

Uhl, C.; and J. B. Kauffman. 1990. Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. Ecology 71: 437-449.

USDA. 1992. Our approach to sustaining ecological systems. Report No. R-1SES_92_02. Missoula, MT: U. S. Department of Agriculture, Forest Service, Northern Region. 15 p.

Wagener, W. W. 1961. Guidelines for estimating the survival of fire-damaged trees in

California.
Misc. Pap. 60. Berkeley, CA: U. S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 11 p.

Waring, R. H.; and G. B. Pitman. 1985. Modifying lodgepole pine stands to change susceptibility
to mountain pine beetle attack. Ecology 66(3): 889-897.

Waring, R. H.; and W. H. Schlesinger. 1985. Forest ecosystems concepts and management. Academic Press, Inc., San Diego. 340 p.

Wickman, B. E. 1992. Forest health in the Blue Mountains: the influence of insects and diseases. Gen. Tech. Rep. PNW-GTR-295. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 15 p. (Quigley, T. M., ed.; Forest health in the Blue Mountains: the influence of insects and diseases).

Wyant, J. G.; P. N. Omi; and R. D. Laven. 1986. Fire induced tree mortality in a Colorado ponderosa pine/Douglas-fir stand. For. Sci. 32(1): 49-59.